FOLIAGE AND NITROGEN DYNAMICS IN A LOBLOLLY PINE (<u>PINUS</u> <u>TAEDA</u> L.) PLANTATION FOLLOWING PRECOMMERCIAL THINNING AND FERTILIZATION

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INTRODUCTION

Increasing demands are being placed on the southern United States to produce more wood and fiber for the nation. Utilization of forest products is expected to more than double by the year 2000 and as much as 60% of the timber required to meet this need is expected to be provided by forests of the South (USDA, 1982).

Loblolly pine (Pinus taeda L.) is considered to be the most important commercial timber species of the South because of its wide range, growth habit, adaptability to site conditions and vast economic use (Goebel, 1975). It ranges across the Coastal Plain and Piedmont, extending from Delaware and Maryland south to central Florida and west to eastern Texas (Figure 1). In Oklahoma, loblolly pine is native only in the southeastern tip of the state in McCurtain County (Fowells, 1965).

Due to the increasing economic importance of loblolly pine, all possible management alternatives to increase production of this timber species should be investigated. One such alternative is precommercial thinning (PCT).

According to Guttenberg (1970), natural regeneration

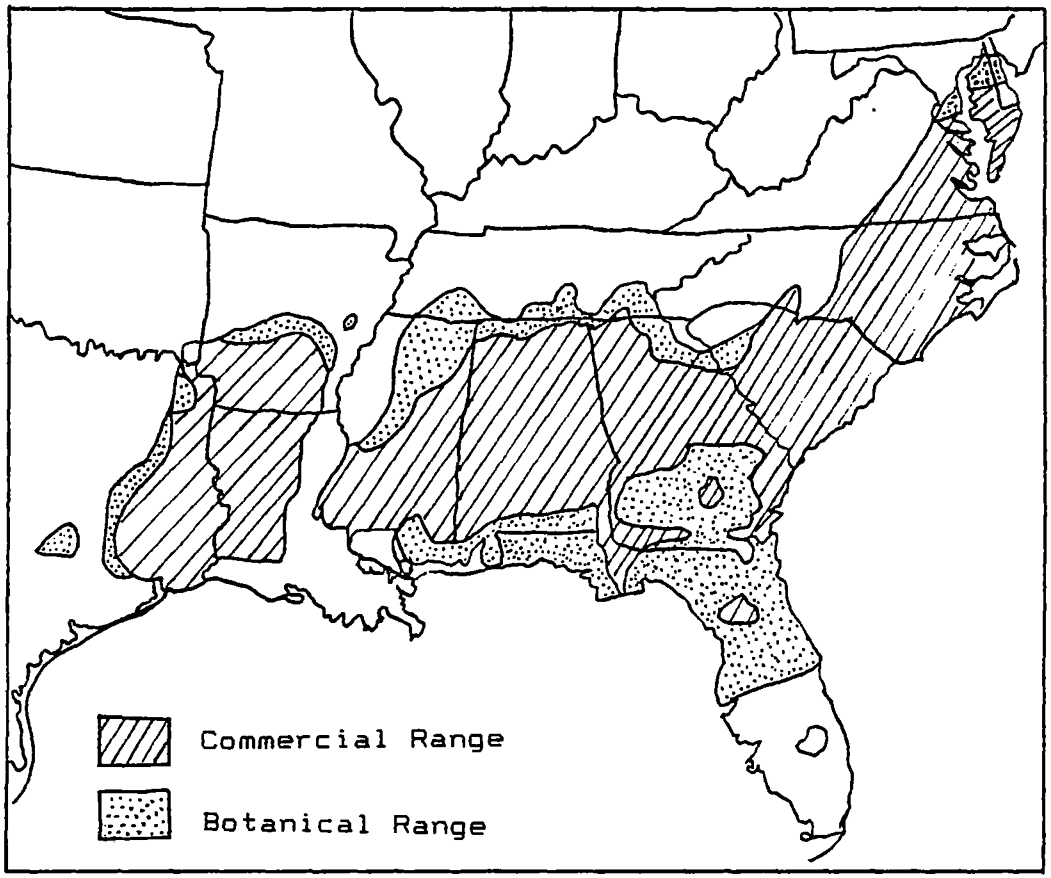

Figure 1. Botanical and Commercial Range of Loblolly Pine

of loblolly pine often results in stands which are overstocked. Artificially regenerated stands are commonly planted at close spacings to ensure good pruning and height growth. Natural thinning of these overstocked stands will occur as the more aggressive trees outgrow and suppress the others-but this is a slow process. Precommercial thinnings release selected trees from competition for water, nutrients and sunlight at an earlier age, thereby allowing them to make rapid and valuable growth. Since loblolly pine grows most rapidly in the early years of its life, release at an early age can maximize growth and development of a pine stand by increasing the efficient use of available resources. The implication is that growth is being concentrated on a reduced number of high quality trees during the rapid growth phase allowing the forester to grow a merchantable tree in a shorter time (Wollum and Schubert 1975).

Although a considerable amount of research has been done to document the beneficial effects of PCT on subsequent growth of the residual stand, little information exists concerning what type of interactions occur in the ecosystem after thinning to stimulate growth. Wollum and Schubert (1975) reported that thinning dense stands of lodgepole pine (*Pinus contorta* Dougl.) at age 43 years improved soil water and nutrient supplies and increased decomposition of the forest floor by increasing soil temperatures and moisture. However, little is known of how thinning affects the ecosystem of young stands in the southern United States. Also, few studies have determined the effects of fertilization and stand density reduction on foliage production and nitrogen (N) dynamics, and the majority of these have been in the western United States. Therefore, a definite need exists for basic information concerning PCT, its affects on the ecosystem, and its use in conjunction with fertilization to maximize the productivity of a site.

For these reasons, a research project was undertaken by the Oklahoma State University Forestry Department in cooperation with the Weyerhaeuser Company to study the effects of PCT on various aspects of the ecosystem in a young loblolly pine plantation. This study was a part of that project.

The primary objectives of this study were as follows: (1) characterize the effects of PCT on the following processes: (a) production and characteristics of the foliage of residual trees (b) nitrogen (N) reallocation among residual trees (c) patterns of litterfall and total annual litter production (d) amount of N returned to the soil via litterfall and (2) study the effects of PCT coupled with fertilization on the above processes.

In addition to satisfying the objectives of this study, the information generated from this investigation will contribute to solving current practical problems. The use of whole-tree harvesting as a means of increasing fiber yield is becoming more common, but these actions could greatly accelerate nutrient removal rates from a site. According to Larsen, et al. (1976), standard whole-tree chipping would about double the biomass and quadruple the N removal from a site compared to a conventional pulpwood harvest. Short rotations also threaten the nutrient status of forest ecosystems. Switzer and Nelson (1972) reported that loblolly pine accumulates nutrients at a peak rate during the first 15 years after establishment; therefore, short rotations would remove nutrients faster than long rotations. Depending upon a site's ability to provide nutrients, successive harvesting could deplete soil nutrients to the point where tree growth is reduced.

With a clearer understanding of soil-tree relationships, fertilization programs or alternative plans may be developed to minimize the nutrient removal impact on forest growth. If rational management alternatives are to be developed, a knowledge of seasonal demands for nutrients, their patterns of accumulation and annual cycling is needed. This study contributes pertinent information to the current understanding of these practical problems.

CHAPTER II

LITERATURE REVIEW

Precommercial Thinning

Efforts to regenerate southern pines often succeed too well, and dense stands result. Previous investigators have shown many ways in which precommercial thinning (PCT) of these dense stands can be beneficial. Early thinnings accelerate diameter growth, reduce rotations, shorten time to the first commercial thinning, reduce susceptibility of trees to insect and disease attack by maintaining tree vigor, and increase production of high quality, more valuable wood by redistributing diameter growth to the larger and more vigorous trees (Grano 1969, Guttenburg 1970, Lohrey 1972, Jones 1975, Mann and Lohrey 1974, Burton 1976, Campbell 1981, Burton and Shoulders 1982, Hughes and Kellison 1982). In addition to increasing production of merchantable wood volume, PCT increases harvesting efficiency at rotation because trees harvested are larger and more evenly spaced. Also, stands are opened up for easier access for protection and silvicultural treatments, and understory browse and cover is increased to help improve wildlife habitat.

Mann and Lohrey (1974) reviewed literature on the question of how PCT effects height growth of southern pines and found conflicting reports. Most studies reported that PCT has no significant effect on height growth (Bower 1965, Keister and McDermid 1968, DeBrunner and Watson 1971, Goebel 1975). Grano (1969) conducted a study in southwest Arkansas in an area with an extraordinarily large catch of loblolly pine reproduction. Trees on plots thinned from 97,565 to 13,338 stems per ha were 1.22 meters taller 14 years after treatment than trees on unthinned plots. On plots thinned selectively to 4,570 pines per ha, average heights 11 years after treatment were 2.44 meters greater than on the controls. This difference was statistically significant at the .01 level, indicating that extreme crowding may hamper the height growth of young loblolly pine. Under these extreme conditions then, PCT may increase the height growth of the residual trees, but tree spacing does not affect height growth in the range of stand densities normally found in managed stands of southern pines.

Height growth is less affected by thinning than is diameter growth because height is primarily under genetic control, whereas diameter is mainly controlled by stand density and site factors (Wollum and Schubert 1975). One of the most important site factors controlling diameter growth is soil moisture availability. In a study by Zahner and Whitmore (1960), a nine-year-old stand of loblolly pine was heavily thinned to determine the effect on diameter growth. Over the five years of the study, diameter at breast height was increased 2.3 times by removing 86% of the original basal area. This increased growth was attributed to an increase in available soil moisture on the thinned plots. On the unthinned plots, diameter growth ceased about mid-way through the growing season because moisture became limiting. Thinning increased the availability of moisture throughout the season thus increasing growth by lengthening the growing season for the residual trees. No differences in height were observed between the thinned and unthinned plots.

In 1972, Lohrey reported on the growth response of an 11-year-old stand of loblolly pine to PCT at age three years. Four levels of selective thinning, three strip thinnings, a combination of strip and selective thinning and an unthinned check were used for the study. Regardless of the method of thinning, average diameters at age 11 years were inversely related to stand density. Diameters did not vary significantly among the methods of thinning used, and it was concluded that thinning method did not effect diameter growth. Residual stand density, not thinning method, was the factor controlling diameter response. Thinning to residual densities above 3,705 trees per ha caused only small increases in diameter growth. Strip thinning to a density of less than 3,705 trees per ha was recommended as the most economical method for stimulating diameter growth. Since strip thinning can be done using high-production machines, it is faster and cheaper than selective thinning.

Increased tree growth following thinning has traditionally been attributed to an increase in light reaching the crown and to an increase in available soil moisture (McClurkin 1961, Langdon and Trousdell 1978). Of considerable importance but less well understood are the status, cycling and allocation of nutrients within the forest ecosystem following thinning. Much research has been done to document the levels of N normally found in young loblolly pine, but less information exists concerning the effects of PCT on the above processes.

The necessity of nutrients, especially N, for normal tree growth is not disputed. According to Creighton (1984), a shortage of N is second only to water as the most common inhibitor of tree growth. Nitrogen is essential for the formation of proteins, vitamins and chlorophyll. Nitrogen deficiencies can result in chlorosis of older leaves and younger foliage in severe cases. The synthesis of important enzymes and chlorophyll is reduced and the photosynthetic surface is decreased. This causes a reduction in photosynthesis which decreases the supply of carbohydrates available for tree growth and wood production, and this may further reduce the uptake of N and other mineral elements.

Although N is required by trees in larger quantities than most other elements, it is usually in short supply in unfertilized soils of the coastal plain. Efficient allocation of N to crop trees must be maintained if a forest is to be productive. Through thinning, excess competition, decomposition rates, and other processes may be manipulated to increase N availability to the residual trees.

Wells and Jorgensen (1973) reported that thinning increased the rate of nutrient cycling by increasing the release of nutrients from the litter. Thinning increases mineralization of the litter by increasing soil temperature and available soil moisture thus allowing higher, more active microbial populations (Creighton 1984). With fewer trees on the site, this increased nutrient release may provide more nutrients for stimulated growth.

In 1959, Boggess reported on the effect of thinning on foliar N concentrations of shortleaf pine (*Pinus echinata* Mill.). Trees in stands thinned to one-third of the original basal area had significantly higher concentrations of foliar N than did trees on unthinned plots. Boggess attributed these results to an increased rate of litter decomposition due to increased sunlight reaching the forest floor. The additional N made available per tree resulted in increased N uptake and therefore increases in foliar N concentrations.

Wollum and Schubert (1975) studied the effects of thinning on the foliage and forest floor of a ponderosa pine (Pinus ponderosa Laws.) stand. Thinning significantly decreased the weight of all components in the forest floor, but the nutrient concentrations of the components were not affected. Eight years after thinning, trees on heavily thinned plots had significantly longer and heavier needle fascicles than did trees on unthinned plots. No increase in the number of needle fascicles per tree was detected. It was observed that trees in thinned stands tended to retain their needles longer than unthinned trees. For these reasons, the authors suggested that the thinned trees would have a larger leaf area which may have increased the photosynthetic capability of the trees leading to faster growth rates. Foliar N concentrations were not significantly affected by thinning, but N content (milligrams/fascicle) was significantly greater in thinned stands. Increased growth of the foliage following thinning may result in a decreased concentration of N or other elements. This phenomena is termed a dilution effect, and may cause trees of thinned and unthinned stands to show comparable concentrations of N although differences in total N content may exist. This effect may be removed by converting N concentrations to absolute contents using estimates of foliar biomass. Chemical properties of the soil were not affected by thinning. However, on thinned stands the limited nutrient supply was being shared by fewer trees. This, in effect, increased the amount of nutrients available to individual trees without increasing the nutrient pools of the site. It was estimated that trees on the heaviest thinned plots had a potential available supply of about 1.82 kg of N while those on unthinned plots had only 0.10 kg.

The nutritional aspects of silvicultural operations are often overshadowed by the emphasis placed on soil moisture-plant relations. It is important to remember that both water and nutrients, especially N, are necessary for tree growth.

Litterfall Production

Litterfall includes leaves or needles, small twigs, branches, bark, fruit, and buds which are cast by standing trees. In the present study, all components of the litterfall were collected and weighed, but only the foliar portion was used for N analysis. According to Spurr and Barnes (1980), litterfall of foliage is the most important source of recycled nutrients in the forest floor of young or intensively managed pine plantations. One key to maintaining the productivity of intensively managed sites is to effectively manage nutrient cycles. Since litterfall is a major pathway by which nutrients are returned to the soil, it is important to understand how cultural treatments affect litter production and nutrient release from the litter. Presently, literature concerning the effects of PCT on the above processes is scarce. A summary of previously reported values for annual litter deposition in unthinned loblolly pine stands is presented in Table I.

Boyer and Fahnestock (1966) found that thinning longleaf pine (<u>Pinus palustris</u> Mill.) stands caused significant decreases in the annual deposition of litter. Plots were thinned to residual basal areas of 2.1, 4.1, 6.2, 8.3, and 10.3 m^2/ha. Three years following thinning, annual litterfall ranged from 1,028 kg/ha under the most heavily thinned stand to 3,364 kg/ha under the least thinned stand. Pine needles made up 70% of the total litterfall. Total litter weight and weight of the pine needle component were significantly related to stand density (0.05 level).

In 1975, Wells and Jorgensen conducted a study in a loblolly pine plantation which was thinned at age 15 years. Prior to thinning, the basal area of the stand was 49 m^2/ha and the annual rate of litterfall was 7746 kg/ha. The stand was reduced to a basal area of 22 m^2/ha, and one year after thinning litterfall production was 3371 kg/ha. Again, annual litterfall production was closely related to the basal area of the stand. Stand density was reduced by 45% which caused a 43% reduction in litterfall.

TABLE I

SUMMARY OF ANNUAL LITTERFALL RATES IN LOBLOLLY PINE

Source	Location	Stand Age	Basal Area	Litter Component: Pine Foliage	Litter Component: Total
		years	m^2/ha	-----kg/ha-----	
Metz 1954	North Carolina	10	23.6	4223	4546
Wells et al. 1972	South Carolina	62	22.0	3892	4585
Nemeth 1973	North Carolina	8	7.8	2639	
		9-10	24.5	3588	
		11	25.9	3698	
Wells et al. 1975	North Carolina	11-15	49.1	6132	7746
		24-27	33.7		5744
		31-39	31.6	4498	6031
Wells et al. 1975	North Carolina	14-17	31.7	4941	6092
Gresham 1982	South Carolina	20	25.7	4368	7796
Curtis et al. 1977	South Carolina	40	21.8		7802
Lockaby 1986	Louisiana	18	31.0		7178

Litter deposition usually follows a predictable pattern with the greatest amounts falling in the autumn and early winter months. In the study by Boyer and Fahnestock (1966), an average of 47% of the annual total litter deposition fell in September, October and November. In the remaining nine months, litterfall averaged approximately six percent per month. Similar results were found by Lockaby (1986) in an 18-year-old unthinned stand of loblolly pine. Forty-eight percent of the yearly total fell in the peak months of October, November, and December (Figure 2).

Variation in the seasonal and/or annual deposition of litter can be caused by extreme environmental factors such as wind storms, ice or snow storms and drought. Insects and disease can also introduce abnormal variation. Van Lear and Goebel (1976) studied the seasonal pattern and quantity of litterfall in a 15-year-old unthinned loblolly pine plantation in the South Carolina Piedmont. Large variations were found in the seasonal pattern of litter deposition, however no reasons for the variation were reported. In the first year of the study, 44% of the annual litterfall occurred during the peak period (October, November and December), and the following year 77% of the annual total was deposited during the peak period.

Annual quantities of litterfall were measured by Gresham (1982) for four years in a mature loblolly pine

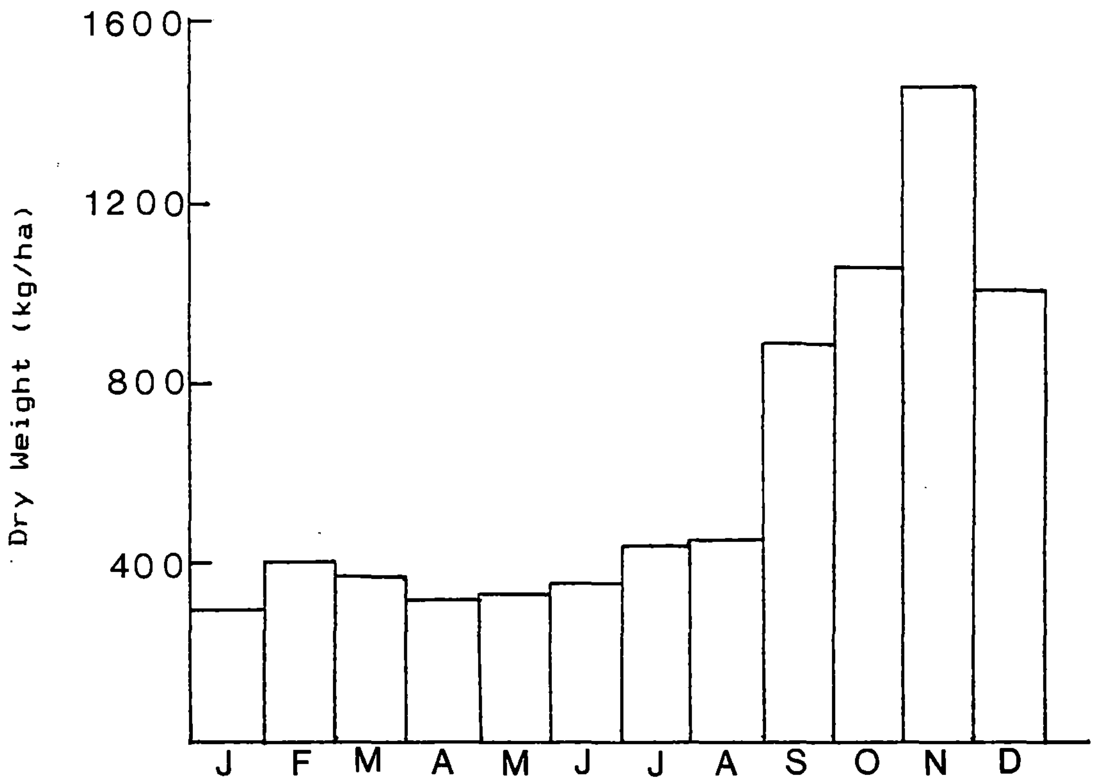

Figure 2. Source: Lockaby, 1986. Seasonal Trends in Litterfall for an Unthinned Loblolly Pine Stand in North Louisiana

stand. During the first three years of the study, litter was deposited at annual rates of 7249 kg/ha, 7350 kg/ha, and 6949 kg/ha, but 9648 kg/ha were deposited during the fourth year. This large increase in litter production was attributed to a hurricane which struck the area in September of that year.

The litter layer which develops under a stand of trees plays a vital role in maintaining site fertility and forest growth by storing and recycling nutrients. In light of this, it seems important to review how cultural treatments affect the decomposition of and release of N from the litter. Litter decomposition is dependent on the population and activity of microorganisms, mainly bacteria and fungi, in the forest floor. The efficiency and abundance of these microorganisms determines the rate of decomposition which in turn affects the availability of nutrients for plant uptake.

Creighton (1984) suggested that thinning would increase the decomposition rate by increasing soil temperatures and available soil moisture. These improved conditions for higher microbial populations would increase the rate of decay thereby enhancing N availability to the residual trees. In 1975, Wollum and Schubert showed increases in litter decomposition following thinning of dense lodgepole pine stands.

Nitrogen fertilization can increase the rate of decomposition, because microbes require N for normal life processes. Nitrogen availability, in part, determines how fast microbes multiply thus affecting population size.

In a study mentioned earlier, Wells and Jorgensen (1975) found that thinning increased the decomposition rate of the litter. After seven years, litter of unthinned stands retained 70-80% of the total N which originally fell to the forest floor. In thinned stands, litter retained less than 50% of the N originally present seven years prior. With fewer trees on the site following thinning, the increased mineralization provided large increases in available N per tree.

Foliage Biomass Estimation

In the past, estimates of crown biomass have been primarily based on whole tree measurements, especially diameter at breast height (DBH) and some measure of crown length or ratio (Rogerson 1965, Loomis et al. 1966, Wells et al. 1975, Van Lear et al. 1984). Recently the practice of whole tree harvesting has increased to utilize the crown material as a fuel source. This could affect the nutrient budget of a site because the nutrient-rich crown material is important for maintenance of nutrient levels. Therefore interest in estimating crown biomass has increased, and estimation based on branch level data is being explored.

Hepp and Brister (1982) presented models for estimating crown biomass based on branch basal diameter, relative height of the branch and stand age. Equations were reported for estimating branch weight (wood, bark and foliage) and branchwood plus bark. Needle weight was found by subtraction.

A model for estimating branch or needle weight was presented by Ek (1979). Weights were predicted based on branch basal diameter, total tree height, height to the branch base and tree DBH. In this study, it was determined that the addition of a spacing or crowding term did not produce significant (p=.05) gains in the model.

In 1976, Larsen et al. reported on the results of a study conducted to estimate biomass and N distribution in 13-year-old loblolly pine with an average basal area of 25.7 m^2/ha. Estimated foliage biomass on a stand level was 9.5 mt/ha, and on a tree level basis it was 6.6 kg.

In a 16-year-old loblolly pine plantation with an average basal area of 49 m^2/ha, Wells et al. (1975) estimated stand level foliage biomass to be 7.98 mt/ha and N content to be 82 kg/ha. The stand was thinned at age 16, removing 64% of the trees. Following thinning, it was estimated that foliage biomass was 3.89 mt/ha. The authors estimated that conventional thinning (leaving branches and foliage on the site) removed 4.6 kg N/ha, but when whole tree harvesting was done 16.1 kg N/ha were removed. It was concluded that complete tree harvesting could remove nutrients at rates high enough to impact subsequent tree growth if soil fertility and nutrient cycling rates of a site are low.

Precommercial Thinning and Fertilization

Although many studies have documented the growth response of pines to precommercial thinning or fertilization, less information exists concerning the combined effects of these treatments on tree growth. In 1963, Curlin published the results of a four year fertilization study conducted in thinned and unthinned stands of shortleaf pine. In the study the following four levels of fertilization were used: (1) control - no fertilization (2) nitrogen - 336 kg/ha (3) phosphorus - 147 kg/ha (4) nitrogen and phosphorus - 336 kg of N and 147 kg P/ha. A given fertilizer treatment on thinned plots produced 1.5 to 2.5 times more response than the same treatment on the unthinned plots. Over the four years of the study thinning plus N fertilization increased basal area growth per tree nearly 300% over trees on plots not thinned nor fertilized. Basal area per tree was 119% greater on plots thinned and fertilized compared to plots unthinned and fertilized. These results prompted the author to conclude that adequate response to fertilization can occur only when stand density is reduced by thinning or when initial stand density is low enough to allow growth to occur unhindered.

Jones and Broerman (1977) conducted a four year fertilization and thinning trial in a 16-year-old loblolly pine plantation. Alone, each treatment caused significant increases in diameter and height growth. Diameter response to the combined treatments was exactly additive, and height growth was better than for either treatment alone. Volume growth was greatest for the fertilization only treatment, while thinning and thinning plus fertilization increased volume growth over that of the controls. Thinning had the advantage of salvaging potential mortality, but reduced the growing stock to a level that limited volume growth response to fertilization.

Youngberg (1975) investigated thinning and fertilization as a way to increase production of ponderosa pine. It was found that thinning produced a greater growth response than N fertilization, and a combination of the treatments produced the best response. Five-year growth response to fertilization was larger on thinned than unthinned plots. The increase in basal area five years after fertilization was 25.3% on unthinned plots and 51.4% on plots which were thinned. These results support the idea presented by Curlin (1963) that thinned stands are more responsive to fertilizer applications, because stand density is at a level which allows growth to occur unrestrained by neighboring trees.

On unthinned stands, fertilization caused a 38% increase in diameter increment over the five years of the study, while thinning alone caused diameter increment to increase by 87%. These results prompted the author to suggest that in dense stands of ponderosa pine, moisture is more limiting than N, but as stand density is reduced moisture becomes less limiting and N becomes the primary limiting factor.

Foliar Analysis

Among the important environmental factors that control the productive capacity of any ecosystem are the levels of essential mineral nutrients available to the crop trees. According to Spurr and Barnes (1980) the leaves or needles are particularly responsive to nutrient supply and foliar analysis has long been popular as a means of assessing the nutrient status of individual trees and entire stands. In this study, foliar nutrient analysis was used to characterize the effects of PCT and fertilization on the N uptake of residual trees. Many previous investigators have reported the concentrations of foliar N normally found in loblolly pine (Table II), but few studies have determined the effects of PCT on foliar N levels.

Proper collection and preparation of sample material are necessary for obtaining an accurate estimate of the

TABLE II

SUMMARY OF FOLIAR NITROGEN CONCENTRATION DATA FOR LOBLOLLY PINE

Source	Stand Age	Location	New Foliage %N	Old Foliage %N
Wells and Metz 1963	5	South Carolina		0.83
Metz and Wells 1965	7-8	South Carolina	1.10	
Wells 1965	5	South Carolina	1.08	
Metz et al. 1966	5	South Carolina		1.04
Miller 1966	8	Miss.	1.32	
Moehring 1966	8	Arkansas	1.27	1.03
	9		1.00	0.90
	10		1.24	0.90
	11		1.12	0.92
Switzer et al. 1966	10	Miss.	1.05	0.82
Wells 1969		South Carolina	1.19	1.06
Wells et al. 1975	16	North Carolina	1.14	0.86
Larsen et al. 1976	13	Alabama		0.85
Van Lear & Goebel 1976	15	South Carolina	1.05	0.82
Lea and Ballard 1982	10-20	North Carolina	1.20	1.11
Van Lear et al. 1984	41	South Carolina	1.07	

nutrient status of forest trees. Several choices are available when a sampling procedure for tree foliage is formulated. In the field, time of year, age of needles, crown position, growth flush, and aspect are factors expected to influence the nutrient content of needles. In the laboratory, tissue drying procedures, grinding techniques, and methods for chemical analysis play important roles.

Variations due to sampling position involve several important considerations: (a) which trees in the stand to sample (b) position in individual tree crowns to sample (c) number of trees to sample. A forest consists of trees of different crown classes even if it is an even-aged stand. Foliage sampling for diagnostic purposes is usually limited to the dominant or codominant trees since these trees are most representative of the site and are of major economic importance. Also, trees of these crown classes tend to show less variation in nutrient levels among trees than over-topped trees growing in various degrees of shading.

Variation in foliar concentrations due to time of sampling involve two considerations: (a) seasonal changes in nutrient quantites and (b) yearly changes in these quantities. Intraseasonal foliar N concentrations depict a predictable pattern; that is, an early season maximum followed by a gradual decline during the growing season and an increase to a fairly steady level during the winter (Figure 3) (Miller 1966). Yearly changes in foliar N levels occur just as annual fluctuations in tree growth rates occur. Nitrogen uptake is related to environmental factors of the site such as air and soil temperature, soil moisture, etc. These factors vary during and between years causing variations in nutrient uptake.

In 1954, White reported on a study designed to help establish a sound basis for standardizing the tissue collecting and sampling procedure. The study was established in a 12-year-old red pine (Pinus resinosa Ait.) and white pine (Pinus strobus L.) plantation in New York. Results suggested that crown aspect is not important when sampling from trees located within fully stocked stands or from trees with relatively equal exposure on all sides. However, uniform sampling techniques dictate that selection of aspect be held constant on all trees sampled.

White's study produced evidence of a reduction in dry matter after air-drying of fresh tissue. This loss in weight was attributed to respiration during the drying process, and can cause large errors in the nutrient concentrations obtained from such material. According to White, this source of error is large enough to require that measures be taken to minimize it in any study involving foliar analysis of pine needles. It is suggested that shortly after collection the needles be

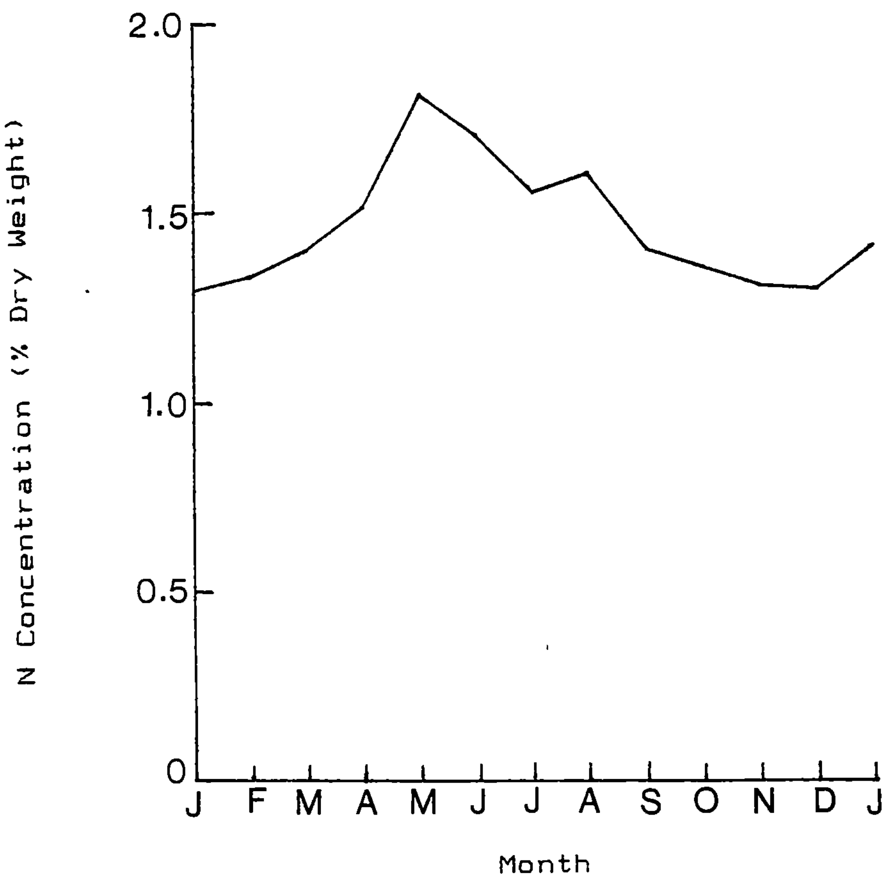

Figure 3. Source: Miller, 1966. Seasonal Trends in Nitrogen Concentrations of Live Foliage for Loblolly Pine

oven-dried at 70°C until brittle. If controlled drying is not possible shortly after sample collection, some type of temporary cold storage in transit will be satisfactory until samples can be dried (White 1954).

With respect to crown position, Wells and Metz (1963) found the middle portion of the crown to be expressive of the average nutrient quantities for the whole crown of five-year-old loblolly pine. The percentage of N in each part of the crown was in the order of lower > middle > upper. The nutrient concentrations determined from sampling the middle portion of the crown were intermediate in all cases. Therefore, the mid-crown position appears to be the most reliable portion of the crown from which to obtain samples since it best represents the general trend of accumulation and loss of N from the crown (Wells and Metz 1963).

One common and well established method to determine N concentrations of plant tissue is the Kjeldahl procedure which has been used in numerous studies involving foliar N analysis (White 1954, Metz et al. 1966, Wells and Metz 1963, Wells 1969, Miller and Miller 1976, Miller et al. 1981). The Kjeldahl method was used for the determination of N in the present study, and this method is detailed in the following chapter.

Fertilization

Two decades ago, forest managers were unsure whether fertilization would increase tree growth sufficiently to be economically feasible. Subsequent fertilizer trials in southern pines of the coastal plain have shown that fertilization can cause relatively large increases in growth.

Zahner (1959) reported on the results of a loblolly pine fertilizer trial conducted in southern Arkansas. Five fertilizer treatments plus a control were used, and the two main treatments of interest were 112 kg of N per ha (N) and 336 kg of N per ha (3N). Fertilization caused no difference in height growth compared to controls. Diameter growth of all fertilized trees was significantly increased although this effect lasted only a few years. There was no significant difference in diameter growth between the N and 3N treatments one year following fertilization, but in the second year trees of the 3N treatment significantly outperformed trees of the N treatment, respectively, growing 23% and 12% more than the controls. The effect of fertilization on current growth had disappeared by the third year.

After the first growing season, trees in all treatments contained significantly higher concentrations of foliar N than did the controls, and trees fertilized with 336 kg of N per ha had higher N concentrations than trees fertilized with 112 kg. For three years following fertilization, trees in the 3N treatment contained higher levels of foliar N than the controls (1.43% vs. 1.12%), but five years after fertilizer application the difference between the 3N treatment and the control had disappeared.

These results, plus the fact that the 3N treatment resulted in 35% more diameter growth and the N treatment in 17% more in the first two years following fertilization, are indications that a second fertilizer application in the third year may have been very beneficial. In a study by Boggess and Gilmore (1959), application of 112 kg of N per ha significantly increased the diameter growth of shortleaf pine the first year after fertilization. Growth continued to increase five years after fertilizer application but at a steadily decreasing rate.

These studies indicate that the effect of N fertilization is positive but short-lived. It has been suggested that additions of N are lost through leaching, may be tied up by microorganisms and are diluted by increases in tree biomass. A fertilizer trial conducted by Moschler, et al. (1970) in the Piedmont area of Virginia tested eight fertilizer treatments applied at the time of planting loblolly pine at a 2 m x 2 m spacing. Ten years after treatment, no differences in survival, height or diameter were detected. Needle length, weight, and N content were not significantly affected by fertilization. These results support the supposition that response to fertilization lasts for only a few years.

In support of the proposed idea that fertilization can cause positive response on a short term basis, the following literature is presented. Windsor and Reines (1973) reported on the six-year results of a fertilization study conducted in a twenty-three-year-old loblolly pine plantation located in Greene County, Georgia. Four hundred and forty-eight kg per ha of 20-10-5 granular fertilizer were applied by airplane, and paired unfertilized plots were established as controls. Radial growth was increased in the first year following fertilization, though the differences in increment were not significant at the .05 level. In the second and third years, radial growth of the fertilized trees was significantly larger than that of the unfertilized trees. By the fourth year there was no significant difference in the diameter response.

Over the six years of the study, average diameter increment was 2.79 cm on fertilized trees and 2.29 cm on unfertilized trees. Although the net increase in diameter increment was small, the significant response to treatment in the second and third years prompted the authors to conclude that another application in the third year might sustain increased growth if the density of the stand is low enough to permit trees to respond. This conclusion is the same as presented by Zahner in 1959.

Moehring (1960) found that one or two annual applications of 112 kg of N per ha significantly increased the diameter growth of eight-year-old loblolly pine and the amount of N in the foliage. Neither response lasted more than two years after the last fertilizer application. The nitrogen concentration of needles returned to the soil as litterfall was similar for fertilized and unfertilized trees. The author suggested that N additions were retained within the tree and, thus, removed from the N cycle.

In general, the sandy soils of coastal plain are inherently infertile, therefore additional nutrients are often required for good tree growth in many intensively managed plantations of this region. Significant growth increases have been obtained in more than two-thirds of the approximately 225 fertilizer trials conducted in the coastal plain from 1954 to 1974 (Pritchett and Gray 1974). However, these responses are usually short-lived and additional applications are required to sustain high growth rates.

Soil and tissue nutrient analysis are an integral part of any fertilizer program. These tests can identify deficient areas and help managers decide where economic growth responses to fertilizers are likely to occur. According to Pritchett and Gray (1974), fertilization of southern pines, coupled with soil and foliar tests to identify deficient sites, holds promise for obtaining economic growth responses.

CHAPTER III

METHODS AND MATERIALS

Study Area

The present study was established in an 11-year-old loblolly pine plantation owned by the Weyerhaeuser Company and located in southeastern Oklahoma in McCurtain County. The stand is pure pine with very few hardwood sprouts intermingled. The most common hardwoods present are sweetgum (*Liquidambar styraciflua* L.), American sycamore (*Platanus occidentalis* L.), water oak (*Quercus nigra* L.), blackjack oak (*Q. marilandica* Muench.), common persimmon (*Diospyros virginiana* L.) and hickory (*Carya spp.*). Common understory vegetative species include common trumpet-creeper (*Campsis radicans* (L.) Seem.), southern dewberry (*Rubus trivialis* Michx.), greenbrier (*Smilax spp.*), and sumac (*Rhus spp.*).

The soil of this area as mapped by the U.S. Soil Conservation Service is a Cahaba fine sandy loam of the Guyton-Ochlockonee association, and the classification is a Typic Hapludult, fine-loamy, siliceous, thermic. It is a deep, nearly level (0 to 1 percent slopes), poorly drained or well drained alluvial soil found on the floodplains and terraces of the Mountain Fork and Little Rivers (USDA 1974).

Actual soil properties and horizonation differed slightly from those of the S.C.S. mapping. The upper 15 cm is a light brown loam which grades into a yellowish-red clay loam from 15 cm to 122 cm (Stogsdill, 1986). Controlling soil wetness is a primary management concern with this soil. Runoff and drainage of water following large storms is slow therefore the site was bedded to ensure good seedling survival after planting.

The climate of McCurtain County is a humid, warm, moist subtropical climate with rains of high intensity. Summers are hot and humid, while winters are usually mild. Long periods of severe cold are rare. The average daily maximum temperature ranges from 12°C in January to 34°C in July and August, while minimum daily temperatures average 1°C in January and 20°C in July. Precipitation averages 119 cm per year with the greatest amount of rain falling in the spring. Late summer to early autumn is the driest period (USDA 1974).

Experimental Design and Treatment Applications

The experimental design used in this study was a randomized block design which included two treatments on each of three blocks. The treatments were three levels of thinning with each level of thinning including a fertilized and an unfertilized treatment (Figure 4). All treatments

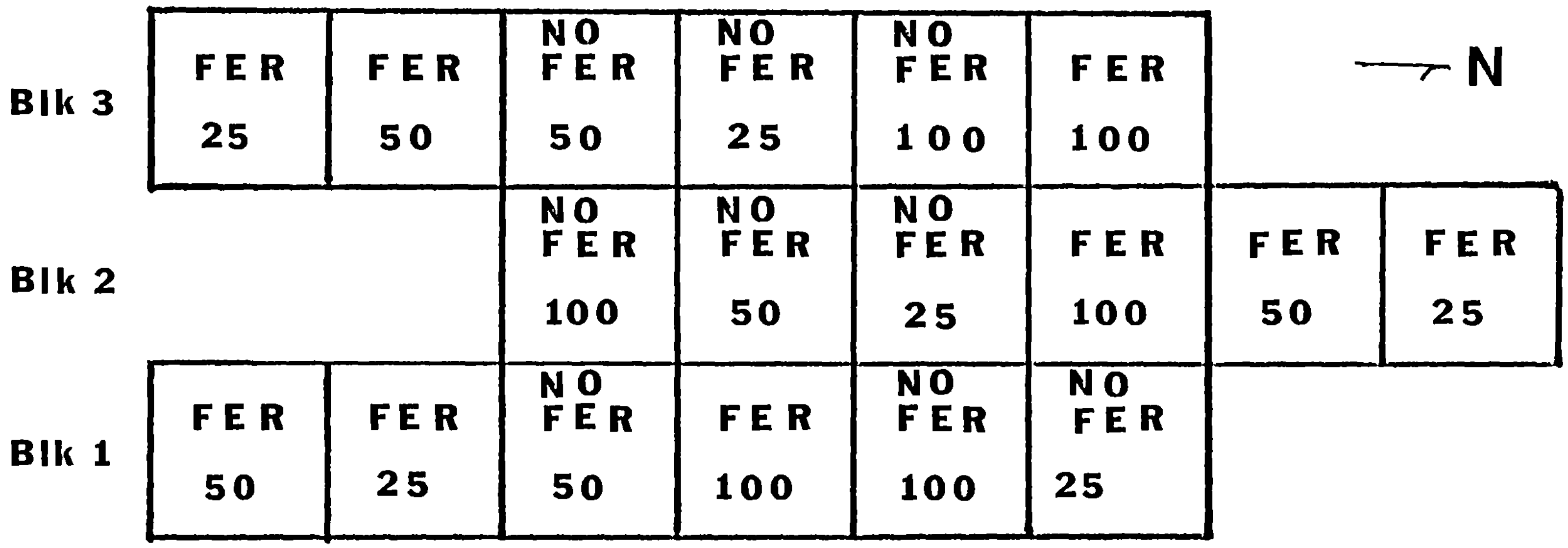

Figure 4. Experimental Design of the Present Study

were applied to 0.1 ha plots randomly located within the blocks. All data were collected from .04 ha interior plots to allow for a buffer zone around each plot. The thinning only treatments were applied in March, 1984 and were as follows for each block :

(a) thin one plot to 25% of the original basal area (25 BA)

(b) thin one plot to 50% of the original basal area (50 BA)

(c) unthinned (100 BA)

This part of the study consisted of nine plots which were thinned to different densities and were not fertilized. Since the treatments were designed to simulate a precommercial thinning, all slash was left on the site. Stand characteristics following thinning can be found in Table III.

A second stage of the study was established in March, 1985. Nine additional plots were thinned to the same residual densities as the original study, and these plots were fertilized with 207 kg of N per ha and 56 kg of P per ha. Stand characteristics of these additional plots are shown in Table IV. In summary, the study consisted of 18 0.1 ha plots in a randomized block design consisting of three blocks and six plots on each block.

TABLE III

STAND CHARACTERISTICS FOLLOWING THINNING IN 1984

Thinning Treatment	Basal Area (m^2/ha)	Trees per ha	Average Height (meters)	Average Diameter (cm)
25 BA	7.45	378	9.0	15.7
50 BA	12.64	692	9.6	15.1
100 BA	25.78	2025	9.2	11.9

TABLE IV

STAND CHARACTERISTICS FOLLOWING THINNING AND FERTILIZATION IN 1985

Thinning Treatment	Basal Area (m^2/ha)	Trees per ha	Average Height (meters)	Average Diameter (cm)
25 BA	8.7	321	10.5	18.9
50 BA	16.8	733	10.5	16.9
100 BA	29.3	2000	9.4	13.3

Sample and Data Collection

Litterfall

In September, 1984 five litterfall boxes were randomly located on each of the nine unfertilized plots. This was accomplished by drawing two random numbers from the random numbers table of Steele and Torrie (1980). Using the north-east corner as a starting point, the first number drawn represented the number of paces into the plot heading west. From this point, the second randomly selected number of paces was used to locate the position of the box by heading south (Appendix B, Figure 9). All boxes were placed in between the beds to reduce variation due to varying bed heights.

The litterfall boxes were 0.70 meters square, 15.0 cm deep, and were lined with 0.32 cm screen on the bottom. Monthly collections of the litterfall began in October, 1984, and were carried out for twelve months. All litter was removed from the boxes by scraping it into paper bags marked with the appropriate number and date.

Results of chemical analysis of the litterfall can be influenced by such phenomena as the leaching effects of rain and incipient decomposition. Both of these sources of variation are directly affected by how long the litterfall remains in the trap. To reduce this variation, collection intervals were held constant.

After collection, litterfall was placed in an oven and dried to a constant weight at 70°C. It was then separated into three categories: pine foliage, pine branches and a miscellaneous category which included mostly hardwood foliage and twigs. The oven-dried, separated litterfall was weighed by category to the nearest 0.1 gram.

As the litterfall was separated, 25 needle fascicles were randomly selected from each box and measured for length in each month except October and November 1984. This was done by stretching the fascicle along a metric ruler and recording the length to the nearest 0.1 of a centimeter. The needle was then returned to the pine foliage category of the separated sample. Lastly, the five pine foliage samples from each plot were composited and ground in a Wiley mill to pass a 1 mm sieve. A subsample of the ground litterfall was obtained and used for the determination of N as explained in a later section.

Live foliage

Monthly foliage sampling of five trees on each of the unfertilized plots began in November, 1984 and was carried out for twelve months. After establishment of the fertilizer plots in March, 1985, three trees on each fertilized plot were sampled in April, July, and October.

The sample trees were selected for uniformity of height and crown form. Healthy, vigorous trees from the dominant and codominant crown classes were chosen. According to the recommendations of several researchers, foliage samples were taken from the middle of the crown on the south side of the tree using pole pruners (White 1954, Wells and Metz 1963, Wells 1965). The foliage was then stripped from the branch and separated into two classes: old foliage and new foliage. For the purpose of this study, the latest flush of the season carrying needles at least 2.54 cm long was considered to be new foliage, and the flush which appeared farthest from the branch tip was considered old foliage. After collection, the foliage samples were placed in a cooler with ice for transportation to the lab in Stillwater. This was done to reduce respiration of the needles which may bias the N concentrations of the samples (White, 1954).

In the lab, a subsample of ten needle fascicles was taken from the new foliage sample of each tree. The length of the fascicles were measured to the nearest 0.1 centimeter as explained earlier for the litterfall needle fascicles. The subsample was then returned to the original sample from which it came. Needle lengths were not measured on the old foliage.

Next, the foliage samples were placed in an oven and dried to a constant weight at 70°C. The new foliage samples were composited by plot and ground in a Wiley mill to pass a 1 mm sieve. Nitrogen was determined on a subsample of the ground material by the Kjeldahl procedure as explained below. The old foliage samples were also composited, ground and analyzed for N.

Nitrogen Analysis

Nitrogen concentrations were determined on ground samples using the macro-Kjeldahl procedure as explained below.

One gram samples were precisely weighed out on 9 cm filter paper which was folded around the sample and placed in an 800 milliliter (ml) Kjeldahl flask. To each flask, 25 ml H_2SO_4, 10 grams K_2SO_4, 0.3 g $CuSO_4$, and three Hengar selenized boiling chips were added. Samples were allowed to digest for two hours, removed from the heat and cooled for 20 to 30 minutes. After sufficient cooling, 300 ml of distilled water were added to each flask.

The digested samples were distilled on a standard Kjeldahl distillation unit. To the sample solution, 75 ml of concentrated NaOH and two small pieces of mossy zinc were added. Fifty ml of boric acid plus an indicator were used to collect the ammonia (NH_3) as the samples were boiled. The distillation proceeded until the receiving flasks contained about 250 ml of solution. This took approximately 30 minutes. The distilled samples were then titrated with weak H_2SO_4 (Normality=0.1290 or 0.1308) to a faint purple end point. Nitrogen concentration of the sample was calculated based on the volume of acid used in the titration using the following formula:

$$\%N=[(N \times V \times 14.008)/SW] \times 100,$$

where N=normality of the titrating acid, V=volume of acid used, SW=sample weight, and 14.008=milliequivalent weight of N.

Biomass Prediction

In mid-March, 1985, a foliar biomass estimation study was initiated. The biomass data were used to convert N concentrations to absolute N contents on a weight per area basis. The purpose was to correct for the dilution effect of crown expansion.

Twenty-two trees from stands adjacent to the study plots were destructively sampled. The trees selected were those which appeared to be representative of final crop trees of the stand. The only other restriction in selecting sample trees was to obtain an even distribution of five cm diameter classes ranging from 10.0 cm to 23.0 cm.

Prior to felling each tree, diameter was measured at 0.3 and 1.4 meter heights. The trees were then cut 0.3 meter above ground level and measured for total height. Beginning at breast height, diameter was measured at 1.5 m intervals to a 2.54 cm top. Height to the base of the live crown and diameter at this point were also measured.

Two sample branches were chosen from each crown position (upper, middle, and lower). These branches were representative of the type of branches present on crop trees, and an even distribution of branch diameters was maintained. For every living branch on the tree, including sample branches, the following measurements were made: height from the ground, branch basal diameter (measured 5.0 cm from the stem), and branch length. The sample branches were removed from the stem and separated into current year's growth and old growth. These samples were then oven dried to a constant weight at 70°C.

The data collected in the biomass sample were used to develop models for predicting foliage biomass on a stand basis by using multiple regression methods with new foliage weight and old foliage weight as the dependant variables.

Foliage weights were predicted based on branch measurements using a nonlinear model adopted from a paper published by Ek (1979). This model was of the form $w=b1 \times d^{b2} \times (H-h)^{b3} \times (H/D)^{b4}$, where d=branch basal diameter, H=total tree height, h=height to branch base, D=tree diameter at breast height and bi's are constants. As the model was being developed and tested, it became apparent that as branch diameter increased the variance of the model residuals (observed foliage weight minus predicted foliage weight) also increased. Therefore, weighting of the foliage weight by branch diameter was done to help relieve this situation.

This model was used to predict foliage weights of all branches on each sample tree, and these weights were summed by tree. The whole-tree foliage weights and measurements were then used to develop a linear equation for predicting total foliage biomass on a tree using the following model: $FW=b_0 + b_1(D^2H)$, where FW=total foliage weight, D^2H=(diameter at breast height)^2 x total tree height, and bi's are constants.

The above model was applied to all trees of the .04 ha plots in each treatment, and foliage biomass per .04 ha was predicted by summing the weights obtained from each tree present. Foliage biomass was then expanded to a kg/ha basis by treatment. Using these predictions it was possible to correct for the dilution effect of crown expansion so that true treatment effects could be determined.

Understory Sampling

As the study proceeded, it became apparent that the heavy cover of understory vegetation which developed in the thinned stands could be affecting the cycling and distribution of N. Therefore, the understory was sampled to determine if it competed with the residual trees for N. A biomass sample was conducted so that the N concentrations could be converted to a kg/ha basis as explained earlier for the tree foliage.

In September, 1985, the biomass sample was carried out by clipping all understory vegetation in ten one square meter subplots in each of the unfertilized plots. The vegetation was separated into three categories: herbaceous, grasses, and woody. It was then dried to a constant weight at 70°C and weighed. In November, 1985, random clippings across each plot were made, and the vegetation was clipped by category as above. The samples were dried, ground in a Wiley mill to pass a 1 mm sieve, and analyzed for N.

Analysis of the Data

The data were analyzed for statistically significant differences among the thinning treatments, fertilizer treatments and interactions between the two. These data were averaged for each treatment, and the treatment means were compared using the Duncan's New Multiple Range Test. Significance was declared at the .05 level of probability. Analysis of variance was used to determine whether the treatments had a significant effect before multiple comparisons were made. This is essentially a process for partitioning a total sum of squares into components with recognized sources of variation. The sources of variation used in the AOV's of this study were as follows: (a) among blocks (b) among treatments (c) among plots within treatments (d) among trees or traps within plots. The AOV's generated mean squares which were used to test hypotheses concerning the treatment means, and interpretations about the effects of the treatments were made from the results of these tests. Regression equations were developed to predict the foliage biomass of trees in each treatment. Procedures for development of these equations were detailed in a previous section.

CHAPTER IV

RESULTS AND DISCUSSION

Litterfall

Seasonal and annual variations in litterfall production are largely influenced by environmental conditions. Needles of loblolly pine usually persist for two growing seasons. Therefore, conditions under which needles develop in a given year will influence the amount, size, and persistence of the needles which will become litter in two years. Also, such phenomena as wind storms, ice storms, and drought may influence the amount and patterns of litterfall produced in a year. Thinning changes the micro-site of a tree and therefore may be expected to influence patterns and total annual accumulations of litter.

In the present study, analysis of variance indicated that thinning had a significant effect on total annual production of litterfall. Annual deposits of litter decreased from 8013 kg/ha in the unthinned plots to 3151 kg/ha in the most heavily thinned (Table V). The litterfall dry weights reported here for unthinned loblolly pine are similar to those presented by Curtis,

TABLE V

ANNUAL PRODUCTION OF LITTERFALL FOR EACH LEVEL OF STAND DENSITY

Thinning level		Litterfall Component: Pine Foliage	Pine Branch	Misc.	Total
		kg/ha			
25 BA	Annual total	2697 C*	193 B	262 B	3151 C
	Annual total per m^2 BA	361	26	35	423
50 BA	Annual total	4323 B	187 C	175 C	4684 B
	Annual total per m^2 BA	342	15	14	371
100 BA	Annual total	6924 A	632 A	458 A	8013 A
	Annual total per m^2 BA	269	25	18	311

* Letters show comparisons among annual totals in each litterfall component. Totals followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

et al. in 1977 who reported 7802 kg/ha (Table I).

On the average, pine needles made up 88% of the total litter, pine branches 6% and miscellaneous material 6% (Table XXIV, Appendix A). In the 25 BA plots, the miscellaneous component was 8.3% of the total, and on the 50 BA and 100 BA plots it was 3.7% and 5.7% respectively. This difference was due to the large amount of understory vegetation which developed in the thinned plots following thinning. Pine branches composed 7.9% of the litter total on the 100 BA plots and 6.1% and 4.0% on the 25 BA and 50 BA plots respectively. Since crown closure is complete in the unthinned plots these results may be attributable to a higher rate of die-off of limbs in the lower crowns of unthinned trees. Also, because crowns of trees in unthinned plots were overlapping, winds may have caused a higher incidence of broken branches in these stands.

Prior to start of the litterfall collections, it was hypothesized that as stand density was reduced litter production adjusted to a kg per square meter of basal area basis would increase. This hypothesis was based on two principles. First, it is well known that trees in thinned stands expand their crowns to reoccupy the site. Tree growth (especially diameter growth) is increased by increasing photosynthetic capacity to take advantage of reduced competition for water, nutrients and sunlight. Increased needle production, either in number of needles or size of needles, may be one mechanism used by trees for crown expansion and expansion of photosynthetic area. Secondly, opening stands through thinning would allow wind, ice, etc. to have a greater impact on an individual needle fascicle.

To test the hypothesis, annual litterfall totals were divided by the number of square meters of basal area per ha to put these totals on a kg per square meter of basal area basis (Table V). It was found that as stand density was reduced litter deposition per square meter of basal area increased. This supports the hypothesis of increased needle production in thinned stands.

Litter deposition usually follows a predictable pattern with the greatest amounts of litter falling in the autumn and early winter months. The pattern of litterfall for the present study is presented in Figure 5. The peak period of litterfall occurred from September thru November, when about 52%, 47% and 44% of the annual total litter for the 25 BA, 50 BA and 100 BA plots respectively was deposited. Unusually high amounts of litterfall were observed in the months of January and July. An ice storm in January and extremely dry conditions in July may have caused this increased needle cast. The patterns of litterfall were similar under each level of thinning; only the amounts produced were significantly affected.

In the months of March, April, July, August, September, October and December, significant differences

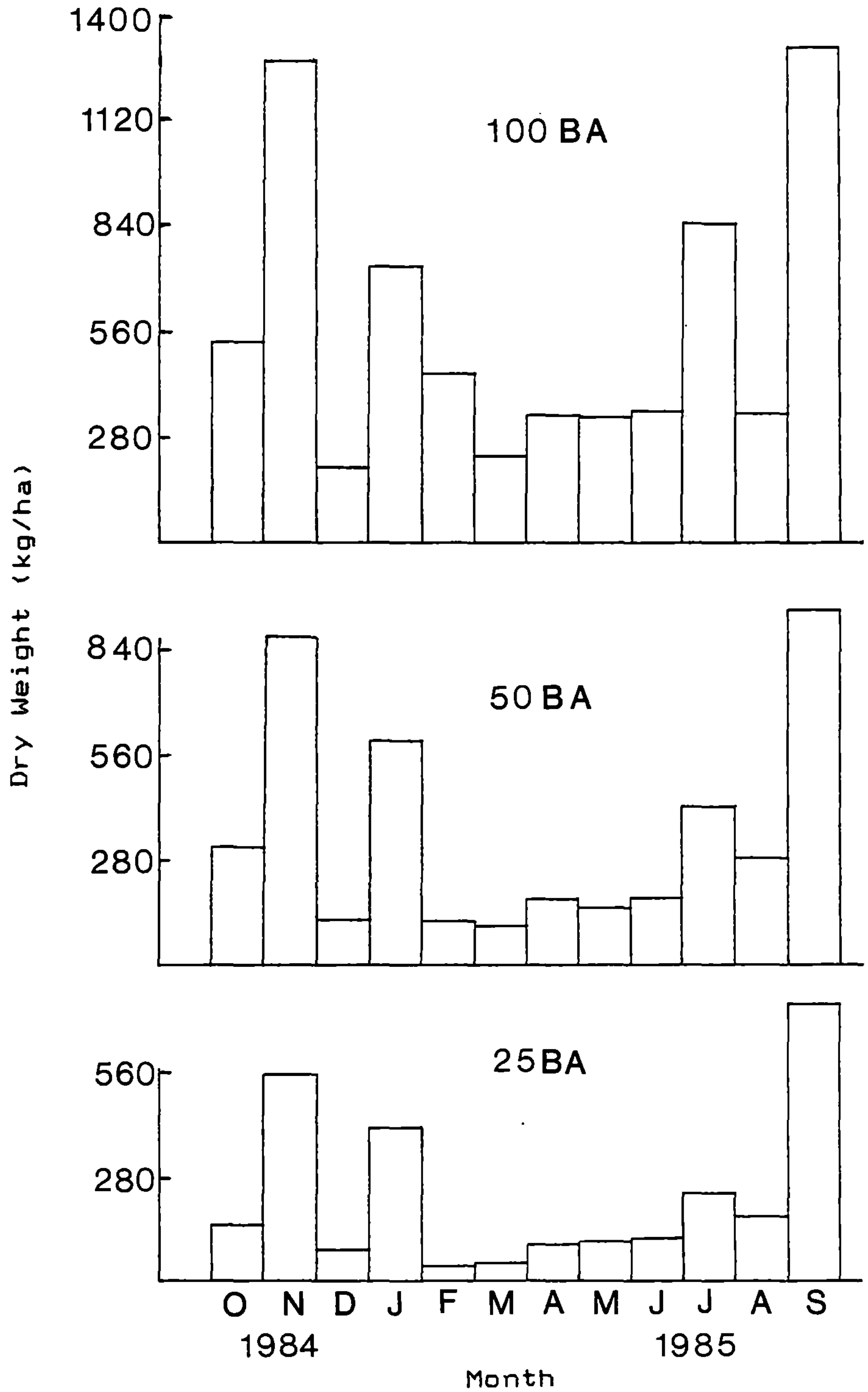

Figure 5. Seasonal Trends in Litterfall at Each Level of Stand Density

in the length of needles cast in each treatment were found (Table VI). Although significant differences developed among the three treatments, few trends or patterns due to thinning were detected. It appeared that the longer, older, more inefficient needles were cast first in the fall, regardless of stand density. In the latter part of the growing season, when conditions became extremely dry, trees of the 100 BA plots appeared to be under severe moisture stress (Figure 10, Appendix B). This caused trees of the unthinned plots to cast some of the shorter, more actively growing needles possibly as an attempt to reduce transpiration and water loss by reducing active leaf area. During these dry conditions, trees of the thinned plots continued to cast only the older, longer needles indicating that less stress was being experienced.

In nearly every month in which samples were collected, thinning had no significant effect on the concentrations of N found in the litter (Table VII). However, some interesting trends developed among the three levels of thinning. During the colder months of the year (those outside the growing season), no trends in N concentrations of the litter were apparent. During the growing season, when temperatures were more favorable for microbial activity and decomposition, N concentrations were consistently highest on the unthinned plots and lowest on

TABLE VI

LITTERFALL NEEDLE LENGTHS ON UNFERTILIZED PLOTS AS AFFECTED BY THINNING

Date	Thinning Level		
	25 BA	50 BA	100 BA
	(cm)		
12/84	15.3 A	15.8 A	15.2 A
1/85	14.5 A	14.3 A	13.8 A
2/85	14.2 A	14.2 A	13.6 A
3/85	13.0 B	14.2 A	13.8 AB
4/85	14.2 B	14.9 A	15.0 A
5/85	14.9 A	15.2 A	15.1 A
6/85	15.1 A	15.3 A	15.5 A
7/85	15.3 B	15.9 A	15.1 B
8/85	15.3 AB	15.7 A	14.8 B
9/85	15.6 A	15.5 A	13.6 B
10/85	16.3 A	16.0 A	15.2 B

* Letters show comparisons among thinning levels within a date. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

TABLE VII

NITROGEN CONCENTRATIONS OF THE LITTER AS AFFECTED BY THINNING

Date	Thinning level		
	25 BA	50 BA	100 BA
	%N		
10/84	0.635 A*	0.613 A	0.592 A
11/84	0.591 A	0.585 A	0.561 A
12/84	0.513 A	0.582 A	0.555 A
1/85	0.464 B	0.502 AB	0.523 A
2/85	0.808 A	0.856 A	0.814 A
3/85	0.963 A	0.962 A	0.891 A
4/85	0.909 A	0.998 A	1.009 A
5/85	0.892 A	0.912 A	0.887 A
6/85	0.777 B	0.822 AB	0.919 A
7/85	0.809 A	0.864 A	0.917 A
8/85	0.606 A	0.689 A	0.753 A
9/85	0.476 A	0.508 A	0.581 A

* Letters following means show comparisons among thinning levels within a date. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

the 25 BA plots. Creighton (1984) suggested that thinning results in higher soil temperatures and increased moisture thereby allowing for higher microbial populations and activity to increase decomposition rates. Average summer soil temperatures at each level of stand density averaged 21.8°C, 20.8°C and 19.1°C for the 25 BA, 50 BA, and 100 BA plots respectively (Figure 6). Therefore, it may be reasoned that litter was broken down fastest on the 25 BA plots. This would increase the rate at which N is released from the litter thus reducing N concentrations and enhancing N availability.

The amount of N transferred to the forest floor through litterfall was directly related to stand density (Table VIII). This was expected since quantities of N returned are primarily controlled by the amount of litterfall accumulated under each level of thinning. The annual quantities of N transferred to the forest floor were 16.08 kg/ha/yr, 28.04 kg/ha/yr and 48.39 kg/ha/yr for the 25 BA, 50 BA and 100 BA plots respectively. The annual rate reported here for unthinned loblolly pine is similar to those presented by Wells and Jorgensen (1975) and Lockaby (1986) who reported 53.2 kg/ha/yr and 41.4 kg/ha/yr respectively.

In the unthinned plots, the large accumulation of N in the forest floor could represent a temporary loss of the element since decomposition rates are relatively slow

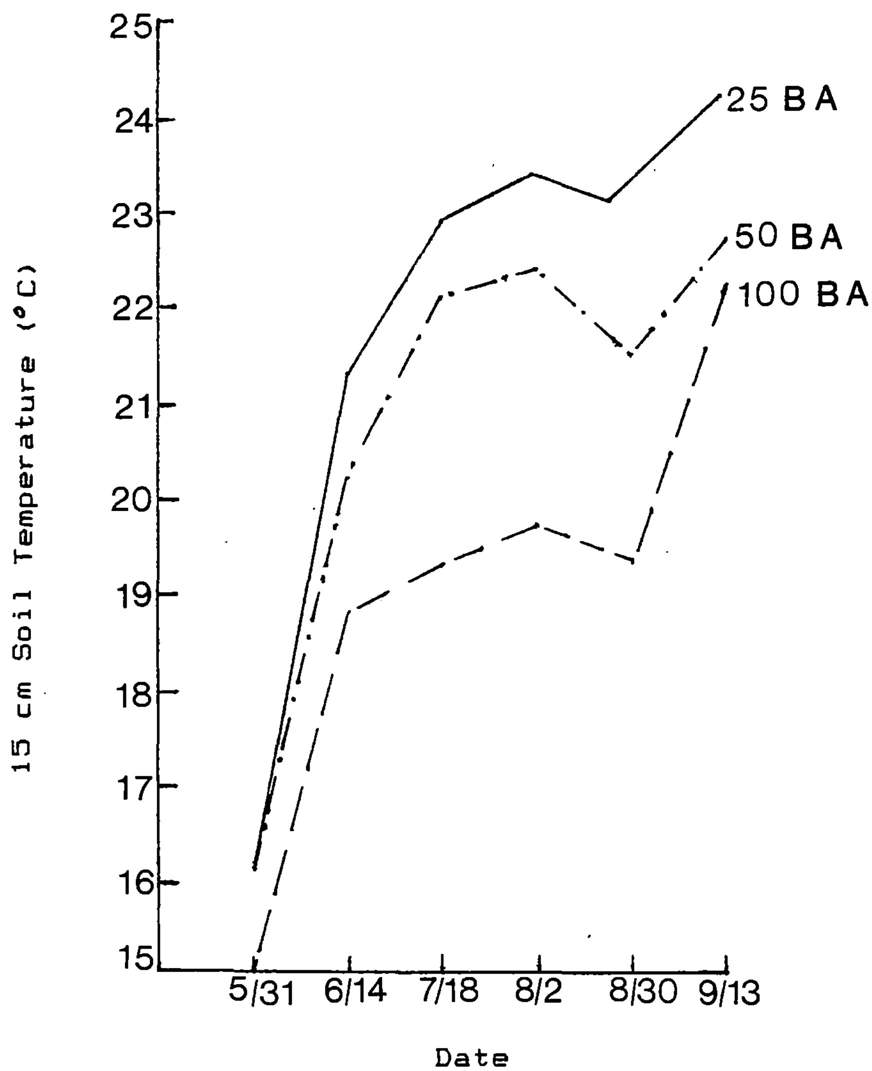

Figure 6. Soil Temperature at the 15 cm Depth Under Each Level of Stand Density

TABLE VIII

MONTHLY NITROGEN CONTENTS OF THE LITTER AND ANNUAL ACCUMULATIONS OF NITROGEN ON THE FOREST FLOOR AS AFFECTED BY THINNING

Date	N Content		
	25 BA	50 BA	100 BA
	kg/ha		
10/84	0.92	1.82	3.14
11/84	3.27	5.11	7.16
12/84	0.41	0.68	1.09
1/85	1.91	2.98	3.83
2/85	0.27	1.07	3.66
3/85	0.45	0.98	2.02
4/85	0.78	1.81	3.44
5/85	0.84	1.40	2.90
6/85	0.81	1.54	3.25
7/85	1.90	3.68	7.73
8/85	1.01	2.00	2.62
9/85	3.50	4.94	7.57
Annual Totals	16.08	28.04	48.39

under the closed canopy of these stands. Turnover of the N returned in the 50 BA and 25 BA plots was faster and therefore less N was tied up in the forest floor.

In summary, the major effects of thinning are to decrease total annual litter production and to increase the cycling rate of N by increasing the release of N from the litter. With fewer trees on the site following thinning, this increased mineralization provides more N per tree without increasing the N capital of the site, thereby possibly reducing the need for fertilization.

Foliage Dynamics

The physiological effects of silvicultural treatments on trees are first manifested as changes in pertinent characteristics of the live foliage. For thinning and fertilization treatments, the characteristics affected may include length of needles and amount of foliar biomass being carried by residual trees. Increases in photosynthetic capacity must occur before increases in merchantable volume due to more rapid diameter and/or height growth can occur. Therefore, it was hypothesized that following thinning and/or fertilization, foliar expansion, manifested as increases in needle length or weight, would occur so that photosynthetic area could be increased to take advantage of reduced competition for moisture, nutrients and sunlight. Also, with fewer trees on the site following thinning and with increases in the nutrient capital following fertilization it was expected that increases in the level of foliar N would occur following the treatments.

Nitrogen Concentrations

Duncans NMR comparison procedure revealed few significant differences in foliar N concentration among trees of the three thinning levels on the unfertilized plots (Table IX). Although not statistically significant, trees on the 50 BA plots consistently had higher N concentrations than did trees on the other two thinning levels (Figure 7). It was hypothesized that trees of the 50 BA plots were under less N stress than trees of the 25 BA or 100 BA treatments due to less competition from understory vegetation and neighboring trees.

Table X shows N concentrations for the old and new foliage of unfertilized and fertilized trees at each level of stand density. Prior to fertilization, trees at all levels of thinning contained N at concentrations above those normally considered deficient for loblolly pine. Leaf (1973) established that N concentrations of the new foliage of loblolly pine below 1.0% to 1.1% were considered to be the critical level below which trees would show a good response to fertilization. Since the lowest N concentration observed during the sampling

TABLE IX

NITROGEN CONCENTRATIONS OF THE LIVE FOLIAGE AS AFFECTED BY THINNING

Date	Foliage Age	N Concentration 25 BA	50 BA	100 BA
		--------------- %N ---------------		
11/84	OF	#A 1.24 A*	A 1.30 A	A 1.18 A
	NF	A 1.38 A	A 1.42 A	A 1.26 A
12/84	OF	A 1.23 A	A 1.32 A	A 1.14 A
	NF	A 1.49 A	A 1.43 A	A 1.27 A
1/85	OF	A 1.36 A	A 1.31 A	B 1.11 A
	NF	A 1.47 A	A 1.47 A	A 1.36 A
2/85	OF	B 1.23 A	A 1.26 A	B 1.05 A
	NF	A 1.44 A	A 1.41 A	A 1.35 A
3/85	OF	B 1.25 A	B 1.19 A	B 1.12 A
	NF	A 1.47 AB	A 1.51 A	A 1.30 B
4/85	OF	A 1.30 A	A 1.31 A	A 1.13 A
	NF	A 1.46 A	A 1.41 A	A 1.29 A
5/85	OF	A 1.55 A	A 1.58 A	A 1.42 B
	NF	B 1.38 A	A 1.44 A	A 1.40 A
6/85	OF	A 1.35 A	A 1.39 A	A 1.29 A
	NF	A 1.26 A	B 1.33 A	A 1.27 A
7/85	OF	A 1.25 A	A 1.33 A	A 1.20 A
	NF	B 1.21 A	A 1.34 A	A 1.16 A
8/85	OF	A 1.06 A	B 1.11 A	A 1.09 A
	NF	A 1.16 AB	A 1.23 A	A 1.13 B
9/85	OF	B 0.97 A	A 1.04 A	B 1.03 A
	NF	A 1.11 A	A 1.16 A	A 1.15 A
10/85	OF	B 1.05 B	B 1.13 A	B 1.05 B
	NF	A 1.25 A	A 1.27 A	A 1.18 A

Letters preceding means show comparisons between old and new foliage within each treatment for each month. Means preceded by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

* Letters following means show comparisons among thinning levels within each age for each month. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

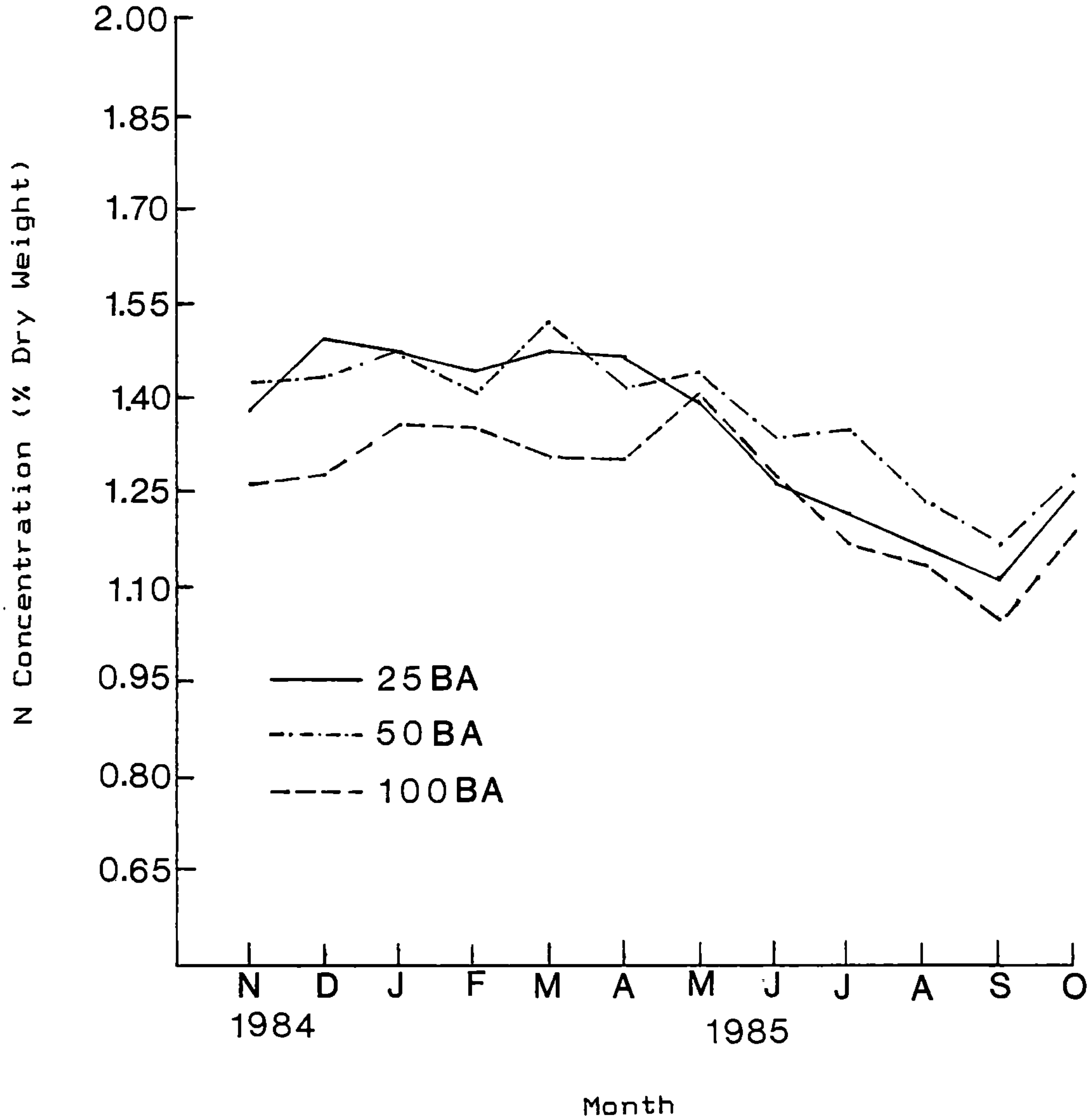

Figure 7. Seasonal Trends in Nitrogen Concentrations of the Live Foliage at Each Level of Stand Density

TABLE X

NITROGEN CONCENTRATIONS AMONG FERTILIZED AND UNFERTILIZED PLOTS THINNED TO THREE LEVELS

		Foliage Age			
	Thinning	Old		New	
Date	Level	No Fert	Fert	No Fert	Fert
		%N			
4/85	25 BA	#A1.30A*	A1.49A	A1.46B	A1.70A
	50 BA	A1.31A	A1.39A	A1.41A	A1.69A
	100 BA	A1.13B	A1.40A	A1.29A	B1.64A
7/85	25 BA	A1.25B	A1.51A	A1.21B	A1.52A
	50 BA	A1.33A	A1.50A	A1.34A	A1.48A
	100 BA	A1.20B	A1.53A	A1.16B	A1.59A
10/85	25 BA	B1.05A	A1.28A	A1.25A	A1.48A
	50 BA	A1.13A	A1.27A	A1.27A	A1.39A
	100 BA	B1.05B	A1.38A	A1.18A	A1.53A

Letters show comparisons among thinning levels within each fertilization treatment. Means preceded by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

* Letters show comparisons between No Fert and Fert treatments within each age, thinning level and date. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

period was 1.11% (Table IX) and most were well above this level, it was concluded that the site was in only marginal need of fertilization. For this reason, large increases in foliar N due to fertilizer additions were not expected.

Response to fertilizer application is usually short-lived because N is quickly lost to competing vegetation, microbes, leaching etc. Approximately six to eight weeks following fertilization, most of the added N has either been taken up by the trees, or lost to one of the sources listed above. Therefore, the speed and efficiency with which trees can take up additions of N controls how well these trees can respond to fertilization. Trees of the 25 BA plots showed a significant increase in foliar N concentration as early as one month following fertilization, and this significant increase continued thru the second sampling period, four months after fertilizer application (Table X). Trees of the 50 BA plots never responded significantly to fertilization, and on the 100 BA plots a significant increase in foliar N was not detected until the second sampling period.

These results may be attributed to root expansion following thinning. The 25 BA plots had an average of 321 trees/ha while the 50 BA and 100 BA plots averaged 733 and 2000 trees per ha, respectively. At such low densities, trees of the 25 BA plots had sufficient space for large increases in root surface area and were therefore able to more rapidly and efficiently take advantage of the additional N. Also, roots of residual trees in thinned stands may have grafted to roots of trees removed, thus, further increasing the root surface area per tree as stand density was reduced.

It is interesting to note that following fertilization all N concentrations of the old and the new foliage were increased to statistically similar levels regardless of stand density and regardless of whether statistical differences existed prior to fertilization. This may have been caused by dilution of the added N because as N was taken up foliar biomass also increased which held the concentrations similar among each level of thinning.

Needle Lengths

In all but three of the twelve months in which foliage samples were collected from trees on the unfertilized plots, current needles were significantly longer on the 50 BA plots compared to the 25 BA or 100 BA plots (Table XI). Prior to the growing season, needles maintained a stable length. In May, when the new flush of the season was first sampled, needles were at a minimum length. Needles in the 25 BA and 50 BA plots grew at a more rapid rate and had attained maximum length by August. However, growth of needles in the 100 BA plots began to level off in July and never quite attained the maximum

TABLE XI

FOLIAR NEEDLE LENGTHS ON UNFERTILIZED PLOTS
AS AFFECTED BY THINNING

Date	Thinning level		
	25 BA	50 BA	100 BA
	centimeters		
11/84	16.1 B*	16.8 A	15.0 C
12/84	15.7 B	16.8 A	15.2 C
1/85	15.5 B	16.5 A	14.9 B
2/85	16.0 A	15.7 A	15.9 A
3/85	16.0 B	16.9 A	15.0 C
4/85	16.7 A	17.0 A	15.2 B
5/85#	6.1 B	6.3 A	5.9 C
6/85	11.5 A	11.4 B	10.5 C
7/85	14.8 B	15.5 A	14.1 C
8/85	17.3 B	17.7 A	15.6 C
9/85	16.7 B	17.0 A	16.1 C
10/85	16.2 B	16.8 A	16.9 A

* Letters compare mean needle lengths among thinning levels within a date. Lengths followed by the same letter are not significantly different at based on Duncan's NMR test at the .05 level.

Began sampling first flush of the current season

length reached by the needles of the thinned plots.

The more rapid development of needles in thinned stands may be attributable to a reduced competition for growing space thereby allowing for increased crown expansion. Another possible explanation for reduced growth of needles in the 100 BA plots concerns moisture depletion rates in thinned versus unthinned stands. In almost every year, water becomes limiting late in the growing season in southeastern Oklahoma (Stogsdill 1986) especially in dense stands where moisture uptake and transpiration rates are high. Thinning helps to distribute available moisture more evenly throughout the growing season and therefore may increase moisture availability during low precipitation periods. This would allow for a more constant supply of water to trees for maintenance of higher growth rates. Because needles of thinned trees reached a higher maximum length in a shorter period of time than those of unthinned trees, the former may have had a larger photosynthetic area allowing for increased tree growth and wood production.

On plots thinned to a basal area of 25%, needle lengths at each sampling period were significantly increased by the addition of N fertilizer (Table XII). In the 100 BA plots, fertilization significantly increased the length of needles in every month except one, and in the 50 BA plots needle lengths were increased significantly

TABLE XII

FOLIAR NEEDLE LENGTHS AS AFFECTED BY FERTILIZATION OF EACH THINNING LEVEL

Date	Fertilization Treatmant	Thinning level 25 BA	50 BA	100 BA
		---------centimeters---------		
4/85	Fert	17.8 A*	18.1 A	16.9 A
	No Fert	16.7 B	17.0 B	15.2 B
7/85	Fert	17.2 A	16.1 A	15.8 A
	No Fert	14.8 B	15.5 A	14.1 B
10/85	Fert	18.6 A	17.0 A	16.9 A
	No Fert	16.2 B	16.8 A	16.9 A

* Letters show comparisons between needle lengths for Fert vs. No Fert on each thinning level within a date. Lengths followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

in only one month. These results suggest that trees of the 25 BA plots were able to take better advantage of the added N than either remaining treatment, possibly due to the low number of residual trees per hectare.

Foliage Biomass

Dry weight of the foliage was predicted in order to estimate foliar N contents for the purpose of studying the dilution effect. The first step in the estimation process was to develop a model to predict the foliage dry weight of each branch on a tree. Branch level predictions were made using a nonlinear, multiple regression model based on the following dependent variables: branch diameter in centimeters (BD), branch height in meters (BH), total tree height in meters (TH), and diameter breast height in centimeters (DBH). A summary of the data used to develop the branch level equations appears in Table XIII. For a more detailed listing of the data see Table XXV, Appendix A. The model used for predicting weight of the old foliage on a branch of a given size and position was as follows:

$$BOFWT(g)=18.1276BD^{2.2682}(TH-BH)^{-1.1765}(TH/DBH)^{0.0182},$$

("R^2") Proportion of variation accounted for=0.41,

$S_{y.x}$=11.32 grams.

The branch level prediction equation used for the new foliage was as follows:

TABLE XIII

MEAN MENSURATIONAL DATA FOR BRANCHES USED IN DEVELOPING PREDICTION EQUATIONS

Diameter Class (cm)	Number of Branches Sampled	Mean Basal Diameter (cm)	Mean Crown Position* (%)
0.50-1.50	29	1.06	45.4
1.51-2.50	51	1.98	41.0
2.51-3.50	23	2.92	26.8
3.51-4.50	18	3.78	18.4
4.51-5.50	5	4.84	2.1
5.51-6.50	2	6.50	1.3

* Calculated as a percent of the total crown length, 0%=bottom of crown, 100%=top of crown.

$BNFWT(g)=31.2213BD^{2.1153}(TH-BH)^{-0.6573}(TH/DBH)^{-0.3725}$,

("R^2") Proportion of variation accounted for=0.81,

$S_{y.x}=17.34$ grams.

The new foliage was more predictable than the old foliage as evidenced by the values of "R^2"; 0.41 for the old foliage versus 0.81 for the new foliage. This was probably due to the fact that old foliage was more susceptible to changes in tree moisture status, nutrient status, degree of shading, etc. which are highly variable factors.

Following prediction of the dry weight of old and new foliage on all sample trees, a linear model was developed to predict total old and new foliage weight on a tree level as a function of D^2H (DBH^2 x total height). The tree level data is summarized in Table XIV, and detailed in Table XXVI, Appendix A. For old foliage predictions, the model was of the form:

$TOFWT(g)=119.2375+(0.3174)D^2H$,

$R^2=0.93$,

$S_{y.x}=184.03$ grams.

The tree level prediction equation used for new foliage was as follows:

$TNFWT(g)=-277.1544+(1.3727)D^2H$,

$R^2=0.94$,

$S_{y.x}=699.19$ grams.

The above tree level equations were applied to each tree in

TABLE XIV

MEAN MENSURATIONAL DATA FOR TREES USED IN DEVELOPING PREDICTION EQUATIONS

Diameter Class (cm)	Number of Trees Sampled	Mean DBH (cm)	Mean Total Height (m)	Mean Crown Length (m)
5.0-10.0	2	6.9	6.7	3.9
10.1-15.0	7	12.1	8.1	4.7
15.1-20.0	9	17.1	11.2	6.4
20.1-25.0	3	22.3	11.8	7.7
25.1-30.0	1	25.6	12.1	7.8

the .04 ha sample plots. The foliage weights of all trees on a plot were summed and expanded to a per ha basis to obtain the stand level predictions of old and new foliage weights.

Estimated dry weights on unfertilized plots ranged from 7.45 mt/ha on unthinned plots to 2.51 mt/ha on plots thinned to 25% (Table XV). On fertilized plots, the estimates ranged from 7.38 mt/ha to 2.00 mt/ha respectively. Unfertilized plots contained almost as much and sometimes more foliage (mt/ha) than fertilized plots. This was primarily due to the fact that unfertilized plots had two growing seasons since thinning, and fertilized plots had only one. The estimated foliage dry weight found in the present study is similar to that presented by Wells et al., (1975) who reported 7.98 mt/ha for unthinned loblolly pine at age 16 years. Also, the estimate is in close agreement with the total annual litter production as should be expected (7.45 mt/ha compared to 6.92 mt/ha).

Because of the varying stocking densities among treatments, the biomass estimates presented in Table XV were adjusted to a per tree basis. These estimates are presented in Table XVI. As stand density is reduced response to fertilization is enhanced, possibly because crowns have more room for expansion, and with fewer trees on the site more of the added N can be taken up by an individual tree. New foliage biomass production (per

TABLE XV

STAND LEVEL FOLIAGE DRY WEIGHTS ON UNFERTILIZED AND FERTILIZED PLOTS FOLLOWING 1985 GROWING SEASON

Thinning	Unfertilized			Fertilized		
Level	OF	NF	Total	OF	NF	Total
	------------------mt/ha------------------					
25 BA	0.54	1.97	2.51	0.41	1.59	2.00
50 BA	0.90	3.21	4.11	1.05	3.93	4.98
100 BA	1.73	5.72	7.45	1.67	5.71	7.38

TABLE XVI

PER TREE FOLIAGE DRY WEIGHTS ON UNFERTILIZED AND FERTILIZED PLOTS FOLLOWING 1985 GROWING SEASON

Thinning	Unfertilized			Fertilized		
Level	OF	NF	Total	OF	NF	Total
	------------------kg/tree------------------					
25 BA	1.48	5.40	6.88	1.64	6.31	7.95
50 BA	1.32	4.71	6.03	1.36	5.10	6.46
100 BA	0.91	3.02	3.93	0.90	3.10	4.00

tree basis) on fertilized plots was 16.8% and 8.3% greater for the 25 BA and 50 BA plots respectively. Old foliage biomass was 10.8% and 3.0% greater for the 25 BA and 50 BA treatments respectively. Fertilization had little effect on foliar biomass production in unthinned stands.
This lack of response may be attributed to the fact that unthinned stands were at complete crown closure when the fertilizer was applied. As reported earlier, Curlin (1963) concluded that trees can only respond to fertilization when stand density is low enough at the time of fertilizer application to allow crown expansion and tree growth to proceed unhindered.

Thinning caused large decreases in the amount of foliage biomass per ha (Table XV). This was expected since unthinned stands were left at complete crown closure and contained at least four times more stems per ha than thinned stands which were not at complete crown closure. Two years after thinning, plots thinned to one-fourth of the original basal area contained one-third as much foliar biomass as unthinned stands, and plots thinned to one-half the original basal area contained slightly more than half as much. These results suggest that trees of the 25 BA plots responded more rapidly to thinning than did trees thinned to 50%.

Foliar biomass on a per tree basis was increased by thinning (Table XVI). Trees on plots thinned to a residual basal area of 25% carried 62.6% more old foliage and

78.8% more new foliage than trees on unthinned controls. On the 50 BA plots, old foliage weight was 45.1% higher and new foliage weight was 56.0% higher than on the controls. These results support the idea that trees on plots thinned to 25% underwent more rapid crown expansion than trees of the 50 BA or 100 BA plots possibly due to less competition for sunlight, moisture or nutrients.

Nitrogen Contents

Average N content per tree of the old and new foliage for each level of thinning on unfertilized plots are presented in Table XVII. Analysis of variance results showed that thinning had a significant effect on foliar N contents. Quantities of foliar N were increased significantly by thinning to residual basal areas of 25% or 50%. There were no significant differences between the 25 BA and 50 BA plots indicating that either treatment was sufficient to reduce competition for N. However, trees of the 25 BA plots consistently had higher N contents than did trees of the 50 BA plots suggesting that as thinning intensity is increased, N reallocation to the residual trees is optimized.

Much larger differences between the three levels of thinning can be seen when the annual patterns in N concentrations (Figure 7) are compared with those of the N contents (Figure 8). It is apparent that

TABLE XVII

FOLIAR NITROGEN CONTENTS ON UNFERTILIZED PLOTS AT EACH LEVEL OF STAND DENSITY

Date	Thinning Level	Foliage Component OF	NF	Total
		---------grams/tree---------		
11/84	25 BA	18.4 A*	75.2 A	93.6 A
	50 BA	17.1 A	66.7 A	83.8 A
	100 BA	10.8 B	38.3 B	49.1 B
12/84	25 BA	18.3 A	80.8 A	99.1 A
	50 BA	17.4 A	67.4 A	84.4 A
	100 BA	10.3 B	38.1 B	48.4 B
1/85	25 BA	20.3 A	79.5 A	99.8 A
	50 BA	17.3 A	69.3 A	86.6 A
	100 BA	10.1 B	40.9 B	61.0 B
2/85	25 BA	18.3 A	78.0 A	96.3 A
	50 BA	16.6 A	66.2 A	82.8 A
	100 BA	9.6 B	40.7 B	50.3 B
3/85	25 BA	18.6 A	79.8 A	98.4 A
	50 BA	15.7 A	71.4 A	87.1 A
	100 BA	10.2 B	39.3 B	49.5 B
4/85	25 BA	19.3 A	79.3 A	98.6 A
	50 BA	17.3 A	66.6 A	83.9 A
	100 BA	10.3 B	38.9 B	49.2 B
5/85	25 BA	23.0 A	74.9 A	97.9 A
	50 BA	20.8 A	67.9 A	88.7 A
	100 BA	12.9 B	42.3 B	55.2 B
6/85	25 BA	20.0 A	67.9 A	87.9 A
	50 BA	18.3 A	62.6 A	80.9 A
	100 BA	11.7 B	38.4 B	50.1 B
7/85	25 BA	18.6 A	65.2 A	83.8 A
	50 BA	17.5 A	62.8 A	80.3 A
	100 BA	10.9 B	35.1 B	46.0 B
8/85	25 BA	15.7 A	62.9 A	78.6 A
	50 BA	14.6 A	57.8 A	72.4 A
	100 BA	9.9 B	33.9 B	43.8 B
9/85	25 BA	14.4 A	60.4 A	74.8 A
	50 BA	13.7 A	54.9 A	68.6 A
	100 BA	9.4 B	34.6 B	44.0 B
10/85	25 BA	15.5 A	67.4 A	82.9 A
	50 BA	14.8 A	59.7 A	74.5 A
	100 BA	9.6 B	35.6 B	45.6 B

* Letters show comparisons among thinning levels within each date and foliage component. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

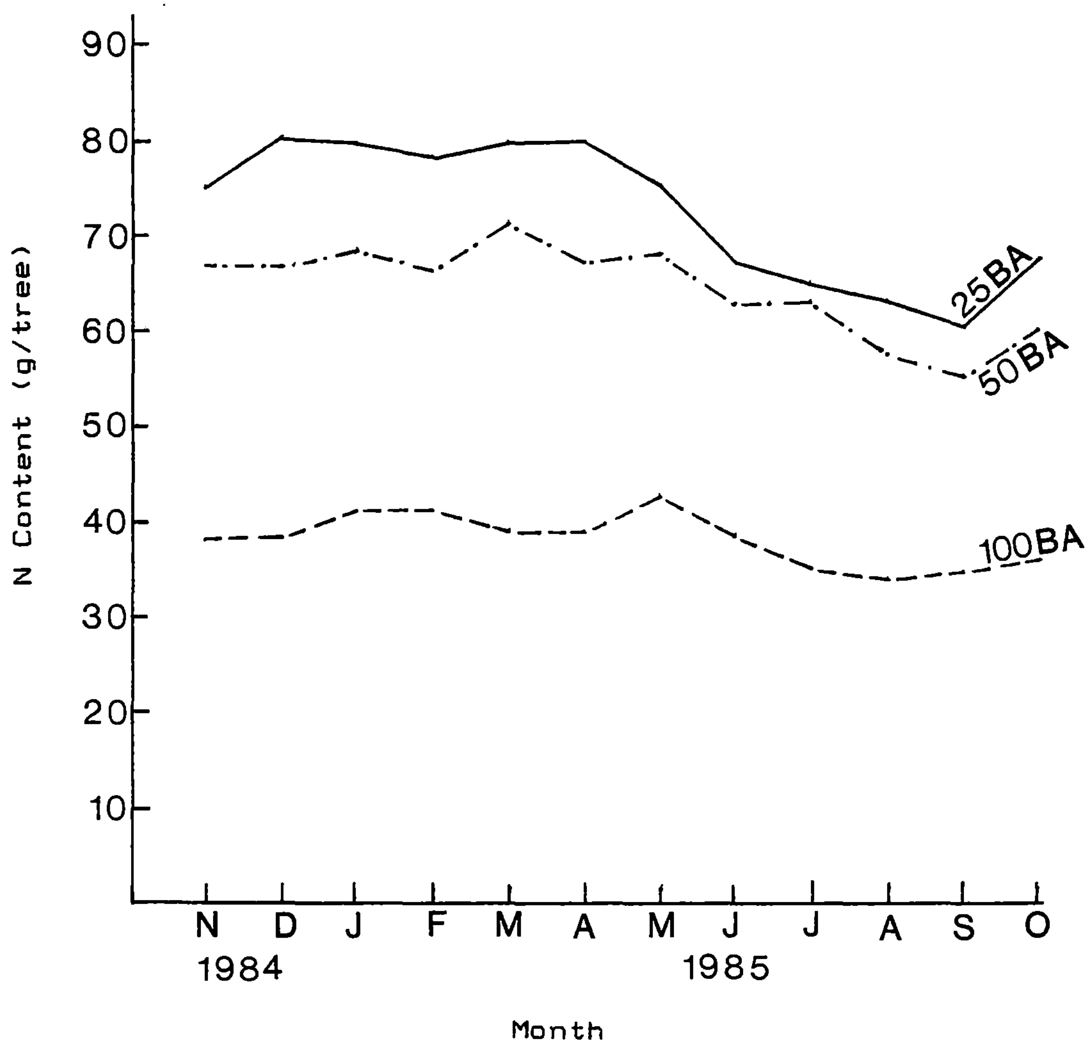

Figure 8. Seasonal Trends in Nitrogen Content of the Live Foliage at Each Level of Stand Density

dilution effect due to crown expansion was occurring. For the annual patterns of N concentrations, thinning caused no consistent or large differences between the three treatments. However, annual patterns of N contents clearly show that as stand density is decreased trees have access to and take up increasing amounts of N. This increased N uptake was masked by the dilution effect of an expanding foliar biomass when expressed as changes in N concentrations. Conversion to absolute N contents removed this effect and allowed true treatment differences to be manifested as shown in Figure 8. Over the twelve months of the study, foliar N contents were increased an average of 75.2% and 90.9% for the old and new foliage respectively by thinning to a residual basal area of 25%. Thinning to 50% caused increases of 59.9% and 69.6% for old and new foliage respectively.

The N content data may help to explain one hypothesis proposed during the discussion of the N concentration results. It was hypothesized that trees in plots thinned to a basal area of 25% were under greater N stress than those of the 50 BA plots because the former had consistently lower N concentrations and a dense cover of understory vegetation. However, N contents were highest in the residual trees of the 25 BA treatment, indicating that the dilution effect of an expanded foliar biomass was more important than understory competition as the factor causing foliar N concentrations to be suppressed in trees of the 25 BA treatment.

Table XVIII shows N contents of the old and new foliage with and without fertilization for each level of stand density. As reported earlier, N concentrations following fertilization were similar among the three levels of thinning. When the dilution effect was removed, however, it was found that trees in thinned stands had significantly higher levels of N following fertilization than did trees of unthinned stands. The N content data indicates that trees thinned to a residual BA of 25% were able to take better advantage of the added N than were trees of the other densities. Prior to fertilization, no significant differences in N content between trees of the 25 BA and 50 BA plots were observed. One month following fertilization, the old foliage of the 25 BA plots showed significantly higher quantities of N than on the 50 BA plots. Also, N contents of the new foliage were significantly higher on the 25 BA plots in the second and third sampling period following fertilization. This increased response to fertilization by trees of the 25 BA plots was again attributed to a larger root surface area per tree as stand density was reduced. Also residual trees of heavily thinned plots had the added advantage of sharing the fertilizer N among fewer individuals. This had the affect of increasing the fertilizer rate for a given tree

TABLE XVIII

FOLIAR N CONTENTS OF FERTILIZED AND UNFERTILIZED TREES THINNED TO THREE LEVELS

		Foliage Age			
	Thinning	Old		New	
Date	Level	No Fert	Fert	No Fert	Fert
		grams/tree			
4/85	25 BA	19.3 A*	24.6 A	79.3 A	107.3 A
	50 BA	17.3 A	18.9 B	66.6 A	86.1 A
	100 BA	10.3 B	12.7 C	38.9 B	50.9 B
7/85	25 BA	18.6 A	24.7 A	65.2 A	95.8 A
	50 BA	17.5 A	20.4 A	62.8 A	75.3 B
	100 BA	10.9 B	13.7 B	35.1 B	49.4 C
10/85	25 BA	15.5 A	20.9 A	67.4 A	93.7 A
	50 BA	14.8 A	17.3 A	59.7 A	70.8 B
	100 BA	9.6 B	12.5 B	35.6 B	38.4 C

* Letters show comparisons among thinning levels within a date, age class and fertilization treatment. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

as stand density was reduced. On the 25 BA plots, the effective fertilizer rate was 0.64 kg/tree while on the 50 BA and 100 BA plots, the rate was 0.28 and 0.10 kg/tree respectively.

Table XIX shows recovery of the fertilizer N one, four and seven months after fertilization at each level of stand density. On a kg/ha basis, trees of the unthinned plots recovered significantly more N than did trees of the thinned plots. This was to be expected since root and foliar biomass of unthinned stands far exceeded that of thinned stands. Although unthinned stands were able to recover more of the added N, the N was shared among a larger number of trees, and therefore response on a per tree basis was limited. Individual trees of thinned stands, especially those of 25 BA plots, had access to and took up larger amounts of the additional N than did trees on unthinned plots.

A larger percent of the fertilizer N was recovered in trees of the unthinned plots compared to thinned plots. This may have been due to sources of N loss which were present on thinned stands but did not exist or existed to a lesser degree in unthinned stands. It was suggested by Cochran (1968) that there may be a temporary loss of N in thinned stands, resulting from microbial needs for N during decomposition of thinning slash and roots of trees removed. Also development of understory vegetation

TABLE XIX

RECOVERY OF ADDED NITROGEN AT EACH LEVEL OF STAND DENSITY

Date	Thinning Level	Recovery Stand	Tree	% of the N Added
		kg/ha	g/tree	
4/85	25 BA	10.68	33.3	5.1
	50 BA	15.47	21.1	7.5
	100 BA	28.80	14.4	13.9
7/85	25 BA	11.78	36.7	5.7
	50 BA	11.28	15.4	5.4
	100 BA	34.20	17.1	16.5
10/85	25 BA	10.17	31.7	4.9
	50 BA	12.53	13.6	6.1
	100 BA	11.40	5.7	5.6

following thinning may represent a loss of N as explained earlier. Thinning causes increased throughfall of precipitation (Rogerson 1963) and therefore may allow a larger portion of the N to be leached from the effective rooting zone before it can be taken up. Even though trees of unthinned stands recovered more of the total N applied, individual trees of heavily thinned stands showed a larger recovery and would be expected to benefit more from fertilization.

Understory Vegetation

Understory sampling to determine the effects of thinning on production of this component was carried out in September 1985. Analysis of variance indicated that thinning had a highly significant effect on total understory yield after two growing seasons (Table XX).
Mc Connell and Smith (1970) found similar results eight years after thinning ponderosa pine in eastern Washington. Average stocking in unthinned stands was 6,916 trees per ha. In stands thinned to 166 trees per ha, understory yield was increased 246%, and the effect of thinning on understory biomass production was significant.

Production of herbaceous vegetation such as southern dewberry (*Rubus trivialis* Michx.), greenbrier (*Smilax spp.*), and sumac (*Rubus spp.*) was significantly increased with each decrease in the level of stand density. Grass

TABLE XX

UNDERSTORY BIOMASS (DRY WEIGHT BASIS)

Thinning level	Understory Category	
	Herbaceous	Grasses
	-------------kg/ha---------------	
25 BA	1447.7 A	122.1 A
50 BA	710.1 B	77.7 A
100 BA	39.3 C	3.0 B

* Letters show comparisons among thinning levels. Weights followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

TABLE XXI

NITROGEN CONCENTRATIONS OF THE UNDERSTORY VEGETATION

Thinning level	Understory category	
	Herbaceous	Grasses
	--------------%N---------------	
25 BA	1.35	1.16
50 BA	1.48	1.35
100 BA	1.35	1.58

production was significantly lower on the unthinned plots compared to the thinned plots. Total herbaceous understory biomass was increased 3583% and 1706% by thinning to 25% and 50% respectively. Increases in grass production due to thinning were 3937% and 2470% on the 25 BA and 50 BA plots respectively.

Nitrogen concentrations of the herbaceous vegetation were not significantly affected by thinning according to analysis of variance at the .05 level (Table XXI). Percent N of grasses, however, decreased as stand density decreased. This may be the result of increased competition from neighboring plants for N in the upper 15 cm of the soil as stand density was reduced and grass cover increased.

Thinning had a significant effect on the N content of the understory (Table XXII). The effect of thinning on N content paralleled the effect on understory biomass production as expected. On plots thinned to 25%, herbaceous plus grassy vegetation contained 20.9 kg of N/ha, which decreased to 11.5 kg/ha on the 50 BA plots and only 0.6 kg/ha on the unthinned plots. In 1972, Switzer and Nelson estimated that a 20-year-old loblolly pine stand required at least 69.2 kg of N per ha to produce the aboveground tree biomass. On the most heavily thinned plots, then, the understory material contained almost one-third of the estimated N required for the plantation to maintain the aboveground biomass. Depending on the inherent

TABLE XXII

NITROGEN CONTENT OF THE UNDERSTORY
(DRY WEIGHT BASIS)

Thinning Level	Understory Category: Herbaceous	Understory Category: Grasses
	--------------kg/ha--------------	
25 BA	19.54 A*	1.41 A
50 BA	10.50 B	1.05 A
100 BA	0.53 C	0.04 B

* Letters show comparisons among thinning levels. Means followed by the same letter are not significantly different based on Duncan's NMR test at the .05 level.

fertility of the soil and the rate of nutrient cycling within the ecosystem this understory biomass could represent a major loss of N to the residual trees of heavily thinned stands.

Competition

As shown in Figure 7, foliar N concentrations of trees on the 50 BA plots always exceed that of trees in either of the other treatments during the growing season. This difference was expected between trees of the 50 BA and 100 BA plots because of the large difference in the number of trees per ha between the two densities. Following the same line of reasoning, it may have been hypothesized that foliar N concentrations of the 25 BA plots would exceed those of the 50 BA plots. This was not the case, and differences in N losses to the understory may help to explain why the observed results were manifested.

Competition from the understory becomes most severe during the growing season when N is more actively taken up and the density of the understory vegetation is increasing. This increased competition for N due to the understory, coupled with the fact that herbaceous biomass was twice as great on the 25 BA plots compared to the 50 BA plots may have reduced the amount of N available to trees on plots thinned to the lowest density. These results suggest that thinning to intermediate densities would make N more available for uptake by residual trees. If vegetation control is used, stands may be thinned to lower densities which would allow trees to be grown to sawlog size in a shorter time period.

The dilution effect of crown expansion is another possible explanation of why foliar N concentrations were lower on the 25 BA plots than on the 50 BA plots. As established previously, trees in thinned stands undergo rapid crown expansion to reoccupy the site. Trees of the 25 BA plots had a larger foliar biomass than trees of 50 BA plots (Table XVI). Even though trees in the 25 BA treatment contained larger amounts of N than those of the 50 BA treatment, the N concentrations were lower in the 25 BA plots because the N was distributed within a larger biomass. Since crown expansion is most rapid during the growing season, the dilution effect may be more prominently manifested during this period.

The N contents of the 25 BA and 50 BA plots were statistically similar, but trees of the unthinned plots contained significantly less N (Table XVII). The unthinned trees appeared to be under severe competition for N due to the high number of stems per acre, and therefore had far lower N contents than did trees of the thinned stands.

Growth Responses

It is well established that tree growth does not show a significant response to silvicultural treatments such as thinning and/or fertilization until at least the second year following treatment application (Curlin 1963). During the first year following treatment, increases in the foliar biomass and/or possibly root biomass must occur in order to increase the photosynthetic capacity of the tree. Then in the second year increases in growth may occur as a function of the increase in photosynthesis. In the present study, attention was focused primarily on the response of the foliage to thinning and fertilization because only one growing season had elapsed since treatment application. Although insufficent time had passed to detect a significant growth response, a few preliminary trends in growth following treatment were observed.

Basal area per tree before and after the 1985 growing season on unfertilized and fertilized plots at each level of stand density is shown in Table XXIII. As stand density was reduced BA growth per tree increased for both the fertilized and unfertilized plots. Fertilization caused no increase in growth on the 100 BA and 50 BA plots, however growth was increased by fertilization of the 25 BA plots. Curlin (1963) reported that adequate growth response to fertilization can only occur when stand

TABLE XXIII

GROWTH RESPONSE TO THINNING AND FERTILIZATION MEASURED AS BASAL AREA GROWTH PER TREE OVER THE 1985 GROWING SEASON

	Unfertilized			Fertilized		
Thinning level	BA/tree before	BA/tree after	% BA growth	BA/tree before	BA/tree after	% BA growth
	------m^2/ha---			-----m^2/ha----		
25 BA	0.024*	0.031**	29.2#	0.027	0.038	40.7
50 BA	0.022	0.026	18.2	0.023	0.027	17.4
100 BA	0.015	0.017	13.3	0.015	0.017	13.3

* Numbers in these columns represent the average basal area per tree before the 1985 growing season.

** Numbers in these columns represent the average basal area per tree following the 1985 growing season.

Numbers in these columns represent the average percent increase in basal area per tree which occurred during the 1985 growing season.

density is low enough to allow growth to proceed unrestricted.

The positive response to thinning and lack of response to fertilization (especially on the 50 BA and 100 BA plots), suggests that some factor (probably moisture) was limiting growth in dense stands. The fact that fertilization caused a response on the 25 BA plots may indicate that as stand density is reduced this factor becomes less limiting and N becomes the primary limiting factor. At the stage of stand development studied in the present investigation, it was concluded that thinning produced a greater growth response than fertilization, and a combination of thinning and fertilization produced the best response.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The short term effects of PCT and fertilization on the production and characteristics of foliage and movement of N through the ecosystem of a young loblolly pine plantation, as determined in the present study, are summarized below. Preliminary growth responses are also listed.

(1) Thinning caused significant decreases in the total annual production of litter, but needle production per square foot of basal area was increased by stand density reduction.

(2) Thinning increased the rate at which N was released from the litter.

(3) Needle fasicles on trees of unthinned plots elongated at a slower rate than those of thinned plots, and never reached maximum lengths attained in the latter.

(4) Thinning significantly increased production of understory vegetation.

(5) Response to fertilization on a per tree basis by uptake of the added N was most rapid and greatest in trees thinned to the lowest density.

(6) As stand density was reduced, foliage biomass production (grams/tree) increased.

(7) The foliar N content of residual trees was significantly higher on thinned plots.

(8) Tree growth was directly related to thinning intensity, and no growth response to fertilization was detected in the 50 BA or 100 BA plots. At the 25 BA level, growth was increased on fertilized plots.

Foliage characteristics and N dynamics were much more sensitive to changes in stand density than to additions of fertilizer. This was probably because the N capital of the site was at a level sufficient for pine growth. Needle fascicle length and foliage weight were significantly increased by thinning. Thinning also increased the level of foliar N in residual trees. The greater mass and more N in needles of thinned trees suggest that these trees might have greater photosynthetic capacity leading to increased wood production.

In retrospect, it may be concluded that much of these data, especially growth data, collected in the present study was preliminary; and therefore, it is recommended that this study be continued for several reasons which are listed below.

(1) Litterfall patterns and annual production of litter are highly variable from year to year because environmental factors which control these processes vary greatly.

Therefore, to obtain a more accurate assessment of litterfall production several years' data should be collected.
(2) Growth responses to thinning and fertilization require at least two years to be fully manifested. Continuing measurements of growth response are recommended to determine if preliminary interpretations reported in the present study hold true.
(3) Because the response to fertilization is usually short-lived, it may be interesting to note when N uptake, foliar expansion and growth response begin to decline and return to pre-fertilization levels. Also, it may be beneficial to study the effects of a second fertilizer application two or three years following initial fertilization.

Establishment of another fertilization/PCT trial on a site more deficient in N may be profitable. It is anticipated that such a study would indicate a larger response to fertilization thereby allowing the investigator to make more certain conclusions about the feasibility or necessity of using both treatments.

Precommercial thinning budgets N for more efficient uptake by the residual trees. If invading understory vegetation is controlled, a larger response to treatment may be expected, and on sites deficient in N, fertilization following PCT may cause large increases in tree growth. All of these cultural treatments can be expensive, therefore potential gains in wood production must be weighed against treatment costs to determine which treatments or combination of treatments best fit the site and situation.

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APPENDIXES

APPENDIX A

TABULATED DATA

TABLE XXIV

PATTERNS OF ACCUMULATION AND ANNUAL PRODUCTION OF LITTERFALL FOR EACH LEVEL OF STAND DENSITY

		Litterfall Component			
Date	Thinning Level	Pine Foliage	Pine Branch	Misc	Total
		--------------------kg/ha	--------------		
10/84	25	145.29 C*	129.99	14.69	289.97
	50	298.02 B	0.50	10.36	308.56
	100	529.00 A	146.96	65.68	741.37
11/84	25	554.29 C	2.17	22.71	579.17
	50	873.86 B	5.01	11.20	890.06
	100	1276.59 A	8.30	62.39	1347.28
12/84	25	80.42 B	.	16.96	97.37
	50	117.69 B	.	24.54	142.26
	100	196.29 A	.	24.95	221.24
1/85	25	412.41 B	.	15.68	428.09
	50	593.57 A	1.23	9.49	604.26
	100	731.56 A	0.50	27.17	759.24
2/85	25	32.62 C	8.95	5.54	47.11
	50	125.39 B	40.96	1.67	168.02
	100	449.96 A	50.44	14.39	514.80
3/85	25	46.95 C	2.94	5.16	55.05
	50	102.60 B	19.50	11.32	133.44
	100	226.65 A	30.33	14.57	271.55
4/85	25	86.69 C	4.62	2.81	94.12
	50	182.00 B	18.36	11.70	212.06
	100	340.94 A	60.21	23.84	424.99
5/85	25	93.93 C	21.91	4.42	120.26
	50	153.00 B	14.07	7.29	174.37
	100	326.80 A	93.23	8.28	428.32
6/85	25	104.17 C	3.49	81.83	189.49
	50	188.58 B	5.20	6.13	199.91
	100	352.94 A	39.37	15.14	407.46
7/85	25	235.90 C	14.50	25.31	275.72
	50	426.88 B	70.38	49.58	546.84
	100	842.60 A	86.15	52.57	981.33
8/85	25	166.20 B	1.82	37.72	205.74
	50	290.24 A	1.91	14.81	306.96
	100	347.55 A	67.37	96.21	511.12
9/85	25	738.05 B	2.00	28.81	768.86
	50	971.40 AB	10.38	16.86	998.62
	100	1302.98 A	49.12	52.36	1404.47
Annual Totals	25	2696.91C	192.40B	261.66B	3150.98C
	50	4323.22B	187.49C	175.00C	4685.71B
	100	6923.88A	631.71A	457.60A	8013.20A

* Letters show comparisons among thinning levels for each month and for the annual totals. Weights followed by the same letter are not significantly different based on Duncan's NMR test the .05 level.

TABLE XXV

MENSURATIONAL AND BIOMASS DATA FOR DESTRUCTIVELY SAMPLED BRANCHES USED IN DEVELOPING PREDICTION EQUATIONS

Branch Number	Basal Diameter (cm)	Crown* Position	Foliage Dry Weight(g) OF	NF
1	1.78	0.0	1.95	36.78
2	1.83	0.0	5.41	31.05
3	2.29	13.6	24.20	132.22
4	2.34	30.7	57.81	109.84
5	2.36	52.8	143.44	65.86
6	2.23	61.4	122.24	73.35
7	2.49	0.0	12.31	39.55
8	2.31	0.0	0.27	14.02
9	1.95	26.3	13.87	20.99
10	1.83	26.3	5.67	43.34
11	2.41	65.9	57.97	120.23
12	1.93	55.7	10.26	67.44
13	3.30	0.9	0.09	128.85
14	3.00	12.3	30.52	169.68
15	1.17	23.2	6.13	23.04
16	2.59	40.0	76.31	189.12
17	1.19	57.7	8.30	37.24
18	1.70	63.6	13.67	84.62
19	3.02	0.8	22.77	147.01
20	3.86	21.0	130.38	352.67
21	2.97	46.8	46.03	209.34
22	3.68	52.4	39.01	337.84
23	3.22	63.5	85.18	159.78
24	2.49	79.4	0.00	170.52
25	3.50	0.0	66.13	101.72
26	2.11	2.7	1.22	35.28
27	2.49	22.8	58.92	110.72
28	1.98	33.3	49.45	109.90
29	0.99	54.3	11.94	18.19
30	1.98	69.4	70.81	73.33
31	3.81	0.0	5.60	53.23
32	1.17	0.0	0.00	14.01
33	1.22	18.0	1.27	29.47
34	2.18	32.0	39.70	115.57
35	1.55	50.7	34.93	51.04
36	0.91	68.0	0.08	24.68
37	3.94	9.1	12.43	259.48
38	2.36	9.1	0.18	65.21
39	1.90	31.7	0.30	100.33
40	1.35	37.6	0.17	55.33
41	1.90	66.7	53.80	93.66
42	1.90	75.8	54.40	77.83
43	2.41	0.0	0.54	19.25

TABLE XXV (Continued)

44	0.96	26.5	0.95	9.78
45	2.79	38.0	71.96	203.43
46	2.03	50.6	70.71	118.28
47	0.63	69.3	3.68	22.35
48	1.73	69.3	36.08	78.03
49	2.62	0.6	0.73	15.89
50	1.83	6.4	1.04	24.66
51	3.02	21.7	13.17	185.79
52	1.02	45.9	0.14	13.17
53	1.27	54.8	6.22	66.78
54	1.52	68.2	41.05	60.87
55	2.54	0.6	2.34	67.32
56	3.25	0.6	16.11	129.69
57	1.57	35.9	5.82	56.87
58	2.79	47.4	92.79	179.28
59	2.16	61.5	48.66	124.92
60	1.60	61.5	30.84	77.01
61	4.88	0.0	10.69	298.35
62	3.50	10.6	0.18	142.62
63	4.19	33.2	7.50	501.21
64	1.70	48.1	7.99	74.58
65	2.41	62.0	9.56	218.01
66	1.29	72.1	26.98	14.15
67	4.19	6.3	22.83	218.49
68	6.60	26.6	134.56	726.65
69	3.78	42.6	18.31	209.92
70	3.15	53.9	110.87	122.82
71	2.23	69.1	47.14	150.07
72	1.98	73.0	35.95	99.21
73	5.16	0.0	1.27	135.39
74	4.19	2.6	38.54	368.25
75	2.92	29.1	71.13	239.03
76	1.45	47.4	10.30	69.53
77	2.36	57.7	73.85	120.62
78	1.07	74.5	2.39	37.50
79	3.10	6.6	5.12	30.40
80	3.58	19.1	15.52	81.26
81	2.79	41.9	17.65	130.90
82	3.63	47.7	73.80	221.76
83	1.50	68.9	4.47	82.44
84	2.08	79.7	53.08	152.67
85	4.32	10.5	140.06	251.65
86	3.12	10.5	27.06	123.63
87	1.70	35.8	24.86	53.37
88	2.95	46.3	117.26	78.40
89	1.40	67.2	1.01	44.22
90	0.76	79.9	0.00	8.53
91	6.40	0.0	141.72	632.94
92	4.06	6.7	43.14	263.82
93	4.78	37.1	262.27	285.00

TABLE XXV (Continued)

94	3.43	46.7	72.19	343.97
95	2.16	73.8	0.00	126.24
96	2.01	81.3	56.37	87.44
67	3.86	0.0	19.71	145.77
98	3.17	16.1	10.12	42.63
99	4.75	21.6	104.81	366.32
100	3.73	31.7	71.15	257.24
101	0.94	73.7	2.18	36.35
102	0.56	81.4	0.00	6.71
103	4.11	0.0	3.64	116.24
104	3.25	15.9	4.07	157.52
105	3.28	33.4	16.43	131.51
106	4.65	48.3	82.83	367.88
107	2.67	70.3	85.26	153.03
108	2.34	74.1	85.45	109.42
109	1.85	16.3	0.32	12.84
110	2.39	26.9	22.60	50.87
111	3.40	37.0	40.42	318.09
112	1.04	45.2	7.27	13.03
113	1.83	64.4	19.77	101.91
114	1.22	72.6	0.00	87.69
115	2.31	0.0	4.23	22.82
116	1.57	6.5	0.51	23.78
117	0.71	24.9	0.00	3.03
118	1.32	59.2	26.50	24.24
119	0.84	68.0	6.65	7.04
120	1.52	68.0	58.35	68.89
121	1.65	0.0	0.80	8.45
122	0.63	5.6	0.48	2.37
123	1.95	30.6	32.41	72.58
124	0.84	40.3	3.53	8.06
125	1.29	53.2	32.00	39.21
126	0.51	66.9	4.90	1.88
127	1.40	0.0	1.25	17.98
128	1.73	0.0	2.19	34.41

* Calculated as a percent of the total crowmn length, 0%=bottom of crown, 100%=top of crown.

TABLE XXVI

MENSURATIONAL AND BIOMASS DATA FOR DESTRUCTIVELY SAMPLED TREES USED IN DEVELOPING PREDICTION EQUATIONS

Tree Number	DBH (cm)	Height (m)	Foliage Dry Weight (g) OF	Foliage Dry Weight (g) NF
1	13.0	9.8	619	1925
2	10.1	9.4	562	1551
3	17.0	11.3	1068	3995
4	16.8	12.4	1105	3234
5	15.9	11.4	1092	3869
6	13.8	10.4	660	2107
7	13.3	9.7	977	2973
8	15.2	10.8	867	2595
9	11.5	9.4	551	1656
10	12.4	8.8	712	2252
11	18.4	10.8	1476	5097
12	25.6	12.1	2688	11283
13	18.3	10.8	1250	4189
14	21.6	11.6	1882	7314
15	21.9	12.1	1480	6036
16	23.4	11.7	2407	9849
17	18.5	10.8	1539	5585
18	18.4	11.7	1263	4634
19	15.3	10.7	691	2234
20	10.4	9.0	333	1001
21	8.6	7.7	232	599
22	5.3	5.8	37	90

APPENDIX B

ADDITIONAL FIGURES

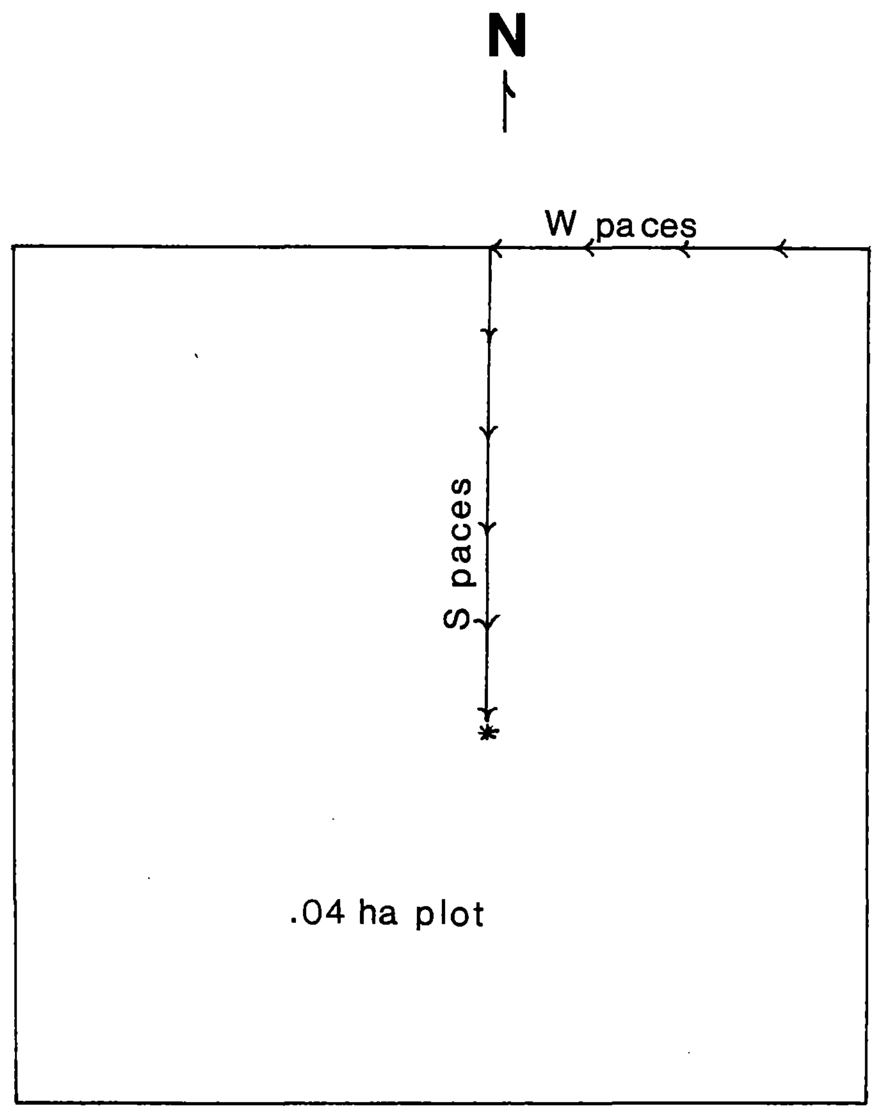

Figure 9. Diagram of the Procedure Used to Position Litterfall Traps

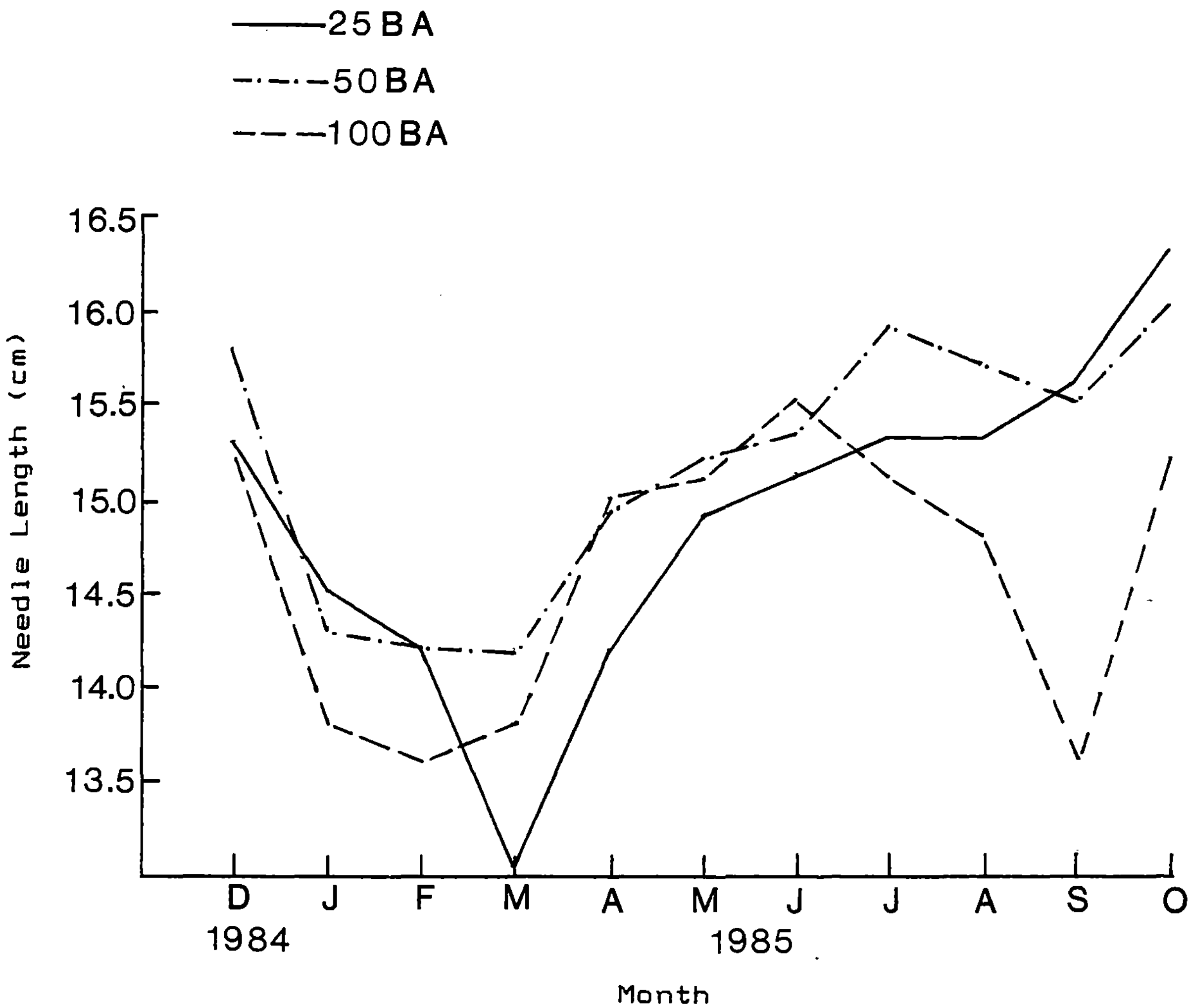

Figure 10. Seasonal Trends in Length of Needles Cast at Each Level of Stand Density

VITA

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Master of Science

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